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Factors Influencing the Pathogenicity of Helminthosporium Sativum

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UNIVERSITY FARM, ST. PAUL

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FACTORS INFLUENCING THE PATHOGENICITY OF HELMINTHOSPORIUM SATIVUM

By Louise Dosdall[1]

INTRODUCTION AND HISTORICAL REVIEW

In 1910 Pammel, King and Bakke (9) described a new *Helminthosporium* disease of barley which they called "late blight." The causal organism was named *Helminthosporium sativum* n. sp. Pammel, et al., had observed the disease in Iowa in 1907 and 1908. In 1909 it was very serious. In the same year, they report that it was also found in South Dakota, Minnesota, and Saskatchewan. These authors describe the disease as follows: "Brown spots of irregular outline occur upon the leaves causing them to turn brown. The leaves are easily broken up, and in some cases completely destroyed. The disease also occurs upon the glumes, spikelets and seed. The straw at harvest is dull brown, and instead of standing erect becomes a tangled mass. The date of ripening of the grain corresponds with the time of full development of the late blight." They observed that there was considerable difference in varietal susceptibility, the degree of infection ranging from 0 to 100 per cent. Late blight was considered the most serious disease of barley in Iowa.

In 1913 A. G. Johnson (7) differentiated clearly the three *Helminthosporium* diseases of barley in Wisconsin, and he designated the one caused by *H. sativum* P.K.B., the "American blotch disease."

Louise Stakman (11), in 1920, showed that a *Helminthosporium* similar to the organism described as *H. sativum* by Pammel, King and Bakke, but isolated from various parts of diseased wheat and rye plants, was capable of causing a serious seedling blight of these hosts, and could also attack the older parts of the plants, namely, the leaves, nodes, culms, roots, glumes, and grains. In addition to wheat and rye, successful infections were obtained on barley and a number of grasses. In the spring and early summer of 1919, serious attacks of seedling blight caused by *Helminthosporium* occurred in practically all the wheat-growing regions of Minnesota.

F. L. Stevens (12), also in 1920, reported that a species of *Helminthosporium* was constantly associated with foot rot disease of wheat in Madison County, Ill. Inoculations with the organism gave positive results. He concluded that *Helminthosporium* was the cause of the disease.

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In January, 1922, Hamblin (5) reported a *Helminthosporium* foot-rot disease of wheat in New South Wales, Australia. The disease symptoms are very similar to those of the true take-all caused by *Ophiobolus graminis* Saccardo, but there are distinguishing characters. Hamblin's description of the foot-rot in Australia corresponds very closely with that of Mrs. Stakman and of F. L. Stevens. His description of the poorly developed root system with an abnormal development of root hairs close to the culm, giving the dead or dying root a "fuzzy" appearance, and the frequent growth of secondary roots above the first node of the affected straws, applies equally well to conditions observed in Minnesota during 1921. In Hamblin's opinion, the *Helminthosporium* disease was responsible for far more damage in 1921 in Australia than was the better known take-all.

In recent years, a foot-rot disease of cereals, particularly wheat, rye, and barley, has been destructive in certain localities in Minnesota. This was especially true on certain peat lands in Anoka and St. Louis counties and on some of the sandy soils in Anoka, Nicollet, and Mahnomen counties. A *Helminthosporium* of the *sativum* type has been consistently isolated from the diseased plants. This organism is very widely distributed throughout the cereal growing region. The severity of its attack apparently must be greatly influenced by ecological conditions. In order to obtain more detailed and accurate information concerning these conditions, a study of the physiology of the fungus, to the extent of its possible correlation with the pathogenicity under given conditions, was undertaken.

PROBLEM

In this study attention was directed primarily to the root- and foot-rots caused by *H sativum*. Little attention was given to secondary infections on leaves and heads. The soil environment was, therefore, of chief concern. In analyzing the factors which might influence the development of a disease of this type, temperature, moisture, and acidity would affect the growth of both the pathogene and the host, and possibly also the reaction between the two. The vigor of the host conceivably might greatly influence the development of a disease caused by a facultative parasite, such as *H. sativum*. The type of soil in which they grew and the available nutriment might, therefore, change the balance between host and pathogene. It is difficult to separate and analyze the individual factors, because certain combinations introduce various complexities which are difficult to interpret.

The following phases of the problem were investigated especially:

1. Relation of temperature to the growth of the fungus, to spore germination, to infection, and to the development of the disease.

2. Relation of hydrogen-ion concentration and temperature to spore germination.
3. Development of the disease in various types of soil.
4. Influence of soil moisture on the development of the disease.
5. Influence of soil fertilization on the development of the disease.
6. Comparison of several root-rotting organisms.
7. Morphological variation in the fungus with regard to its specific identity.

METHODS

SOURCE OF PATHOGENE

During the spring and summer of 1920, tissue cultures were made from lesions caused by *Helminthosporium* on cereals and grasses. Twenty-two strains (isolations from various parts of different hosts or from different localities) of the *sativum* type were obtained from the roots, stems, nodes, leaves, and kernels of barley; from the roots, stems, leaves, and kernels of wheat; and from leaf spots of various grasses. Material was obtained from Anoka, Clay, Mahnomen, Nicollet, Ramsey, and St. Louis counties in Minnesota; from Tennessee, and from Spruce Grove and Edmonton, Alberta.

Seven of these strains were selected for preliminary inoculation experiments. As a virulent root-rotting organism was desired, only soil inoculations were made. Four-inch pots filled with soil were treated with live steam for two hours on each of three successive days. Six pots of such soil were inoculated with each of the various strains of *Helminthosporum.* For this purpose, spores were scraped from the surface of potato dextrose agar cultures and mixed with water. The suspension of spores was poured over the soil, and the pots were incubated for several days. Three pots which had been inoculated with each strain were then sowed with Marquis wheat and three with Manchuria barley (Minn. 105). Some infection was obtained in each case, on both the leaves and the roots. (The check plants were slightly infected, as the seed had not been treated.) The plants inoculated with strain 82a, however, were decidedly more heavily attacked than the others. This was especially true of the barley plants. A *Helminthosporium* of the *sativum* type was re-isolated from lesions on both the barley and the wheat. A single spore culture was then made from the original 82a culture, and all subsequent work was done with this single spore strain.

Culture 82a was originally isolated from the darkened base of badly stunted barley plants sent to the laboratory from the peat plots on the Fens experimental field, St. Louis County, Minn., in the summer of 1920. A similar *Helminthosporium* was isolated from the nodes, sheaths, and blades of the same plants.

In addition to *H. sativum, Alternaria* was frequently obtained from blackened kernels and nodes; a pink *Fusarium* was sometimes found on the base of the stem and roots; and *Helminthosporium teres* Sacc. was occasionally isolated from the leaves and stems.

SELECTION OF HOST VARIETIES

In all experiments, the effect of the fungus on wheat and barley only was studied. In most cases where barley was tested, both Manchuria (Minn. 105) and Lion (Selection) were used. Manchuria is the barley most commonly grown in Minnesota. It is somewhat resistant to *H. sativum,* as shown by the work of Pammel, King and Bakke (9), of Hayes and Stakman (6), and of Christensen (3). For this reason it was used in the breeding work of Hayes and Stakman. It was crossed with the smooth-awned Lion, which is very susceptible to *Helminthosporium,* in an attempt to obtain a high yielding, smooth-awned, resistant variety.

Marquis (Minn. 1239) was used in most of the experiments with wheat. In some cases Haynes Bluestem (Minn. 169) also was used.

CHECK PLANTS

Since it is difficult to obtain seed entirely free from *Helminthosporium,* especially in susceptible varieties, it was necessary to treat the seed in order to reduce infection in the check plants to a minimum. Silver nitrate was found to be the most useful disinfectant because the seed coats of both barley and wheat are impermeable to it (10), and the seed can be soaked for a long time in the solution without being injured. It also is more effective, especially against *Helminthosporium,* than mercuric bichloride. For experimental purposes, the method of seed treatment followed was essentially that recommended by Schroeder (10). The seed was dipped in 50 per cent alcohol to remove the air from the surface, soaked over night in N/100 silver nitrate solution, dipped in a dilute sodium chloride solution to precipitate as insoluble silver chloride the silver nitrate remaining on the surface of the seed, washed thoroly in running tap water, and dried. Such treatment reduced the germination of Lion barley from 90 per cent to 78 per cent, and of Marquis wheat from 99 per cent to 97 per cent.

SPECIFIC IDENTITY OF THE PATHOGENE

Three species of *Helminthosporium* are known to occur on barley in the United States. These are readily distinguished on the host by the symptoms. *H. gramineum* Rabh. causes the systemic stripe disease characterized by long, narrow, yellowish to brownish spots on the leaves and sheaths. Many spots often coalesce to form parallel striations which run more or less the entire length of the blade and often down the sheath. Eventually the leaves may be reduced to shreds. *H. teres.* Sacc. and *H. sativum* P.K.B. both cause local lesions which are characterized by peculiar blotches on the leaves. *H. teres* causes the European blotch or net blotch disease. The spots are yellowish brown in color, irregular in shape, and are scattered on the leaves. When held to the light, a characteristic net work is apparent. *H. sativum* causes the spot blotch disease characterized by irregular reddish brown spots on the leaves. The spots are usually longer than they are broad, and, when abundant, may tend to form stripes.

These three species also may be distinguished readily by their growth on potato dextrose agar. *H. gramineum* grows slowly, forms a fluffy, aerial mycelium which does not sporulate (at least not readily), and usually gives the medium a reddish or purplish tinge. *H. teres* also grows rather slowly. The mycelium grows very close to the surface of the agar. The color of the reverse side of the colony is greenish black. Grayish white tufts of mycelium are formed irregularly on the surface of the colony. Cylindrical, thin-walled spores are formed, but usually they are not abundant. In contrast to both these species, *H. sativum* grows very readily and sporulates abundantly, forming a flat, black or greenish black colony on agar. The abundance of conidia gives the surface a powdery appearance. Organisms similar to the one isolated from typical barley spot blotch have been isolated hundreds of times by workers in this laboratory from various parts of barley, wheat, and rye plants, and from numerous grasses.

Pammel, King and Bakke (9) described the spores as cylindric in shape, straight or curved, slender, widest at the middle, from 105 to 130 microns in length by 15 to 20 microns in width, pale greenish gray to dark brown in color, with 7 to 14 cells. Later workers have found much shorter spores, altho observations on shape agree fairly well. Johnson (7) states that the spores are narrowly spindle-shaped, usually more or less curved. Mrs. Stakman (11) describes the spores of the organism with which she worked as either straight or curved, dark blue-green to brown in color, averaging 41 by 20 microns in size, and containing from 3 to 8 septa. Two types were isolated from diseased wheat: one a fuscous type measuring 35 by 22 microns and containing from 3 to 4 septa; the other straw-colored to fuscous, measuring 60 by 20 microns, and containing from 4 to 7 septa. Both of the latter are described as elliptical in shape.

Stevens (12) makes the following statement regarding the form causing the foot-rot of wheat: "The spores, observed as grown on autoclaved wheat leaves or stems in humid air, are from 24 to 122 microns long, the majority of them falling within the limits 80 to 90 microns, with septa or pseudo-septa varying from 0 to 13, usually 5 to 10. The spores are usually typically thickest in the region about midway between the base and the middle point of the spore, approaching a narrow or broadly elliptical shape, tapering somewhat toward each end. They possess an outer dark wall that is thin and extremely fragile and an inner, colorless, thick wall that is frequently soft and gelatinous . . . The spores usually, perhaps always, germinate either from one or both ends, not laterally, and are functionally only one-celled."

After making a large number of isolations from *Helminthosporium* lesions on barley, wheat, and rye, great variations were found in the size of the spores of the various cultures, altho they resembled each other more or less in shape and color. In order to find out just what variations might be expected in one strain, as a guide to the interpretation of the species, a single spore was again isolated from culture 82a and a biometric study was made of the spores produced under various conditions.

The single spore was planted on a potato dextrose agar slant and incubated at 24° C. for ten days. Transfers were then made to potato dextrose agar and to ripe autoclaved barley heads. Agar cultures were incubated at the following temperatures: 5°, 14°, 18°, 24°, 28°, 32°, and 36° C. The cultures grown at 5° and 36° did not produce spores. The barley head cultures were incubated at 24° C. Fresh barley leaves were taken from the greenhouse, placed in moist chambers, inoculated with spores of the same culture, and incubated at 24°. The length of time required for the cultures to sporulate at the different temperatures varied considerably; those at 24°, 28°, and 32° were ready for measurement in 16 days, while those at 14° required 37 days.

TABLE I

Variations and Constants for Length of Spores of *Helminthosporium sativum* Obtained from Measuring Populations of Different Size

Conditions under which spores were produced		Distribution in classes (microns)												No. of spores measured	Mode	Mean	Standard deviation	Coefficient of variability
Temperature, degrees C.	Medium	10	20	30	40	50	60	70	80	90	100	110	120					
32	Potato dextrose			3	7	14	32	29	14	1				100	60	62.30 ±0.85	12.56 ±0.60	20.16 ±1.18
32	Potato dextrose	1	13	8	34	52	92	77	22	1				300	60	57.44 ±0.57	14.69 ±0.40	25.57 ±0.75
32	Potato dextrose	1	16	15	48	73	149	136	57	4	1			500	60	59.66 ±0.45	14.81 ±0.31	24.82 ±0.56
32	Potato dextrose	3	29	25	94	191	281	268	103	6				1000	60	59.07 ±0.31	14.34 ±0.22	24.27 ±0.39

Spores from these various sources were then measured for length. In all cases, measurements were made with a Bausch and Lomb microscope, using the 4 mm. objective and an eyepiece micrometer calibrated so that one space was equal to 3.4 microns. It was observed that at an extreme temperature, such as 32° C., there was a great deal of variation in length and a large number of measurements would be required to obtain a normal curve. Data were therefore recorded for the measurements of 100, 300, 500, and 1000 spores. From these data the mean was calculated for each group and the differences were compared in relation to the probable errors, according to the methods given by Babcock and Clausen (2). These data are summarized in Tables I and II. For 100 spores the mean was found to be 62.30 ± 0.85 microns; for 300 spores 57.44 ± 0.57 microns; for 500 spores 59.66 ± 0.45 microns; and for 1000 spores 59.07 ± 0.31 microns. Their accuracy can be seen by comparing these results with their probable errors. In Table II the comparison of the means for 100 and 300 spores with the means of each of the other three groups, shows that the difference between any two is from 3 to 5 times the probable errors of the difference. This borders on the verge of a significant difference, so that 100 or perhaps even 300 spores are scarcely enough to use as a basis for drawing conclusions. When the mean for 500 spores is compared with that for 1000, the ratio is 1:1. The results obtained by measuring 1000 spores are only very slightly more accurate than those obtained by measuring 500 spores. The difference is certainly not great enough to necessitate the measurement of the second 500 spores.

TABLE II

SUMMARY OF COMPARISONS BETWEEN MEANS AND COEFFICIENTS OF VARIABILITY FOR LENGTH OF SPORES OF *Helminthosporium sativum* OBTAINED FROM MEASURING POPULATIONS OF DIFFERENT SIZE (FROM DATA SUMMARIZED IN TABLE I)

Conditions compared	Means		Coefficients of variability	
No. of spores	Difference	Difference divided by the probable error of the difference	Difference	Difference divided by the probable error of the difference
100 and 300	4.86±1.02	5	5.41±1.73	3
100 and 500	2.64±0.96	3	4.66±1.31	4
100 and 1000	3.23±0.91	4	4.11±1.24	3
300 and 500	2.22±0.72	3	0.75±0.93	1
300 and 1000	1.63±0.65	3	1.30±0.85	2
500 and 1000	0.59±0.55	1	0.55±0.68	1

These comparisons are perhaps brought out more clearly by the curves in Figure 1, in which the data obtained from measuring the different lots of spores have been plotted after grouping the measurements into 10 micron classes. The lowest curve, representing 100 spores, very clearly does not give a true index of the lower extreme of the total population. This explains why the mean obtained from 100 spores is too high. The three succeeding curves show that, as the number of individuals increases, the curve gradually approaches

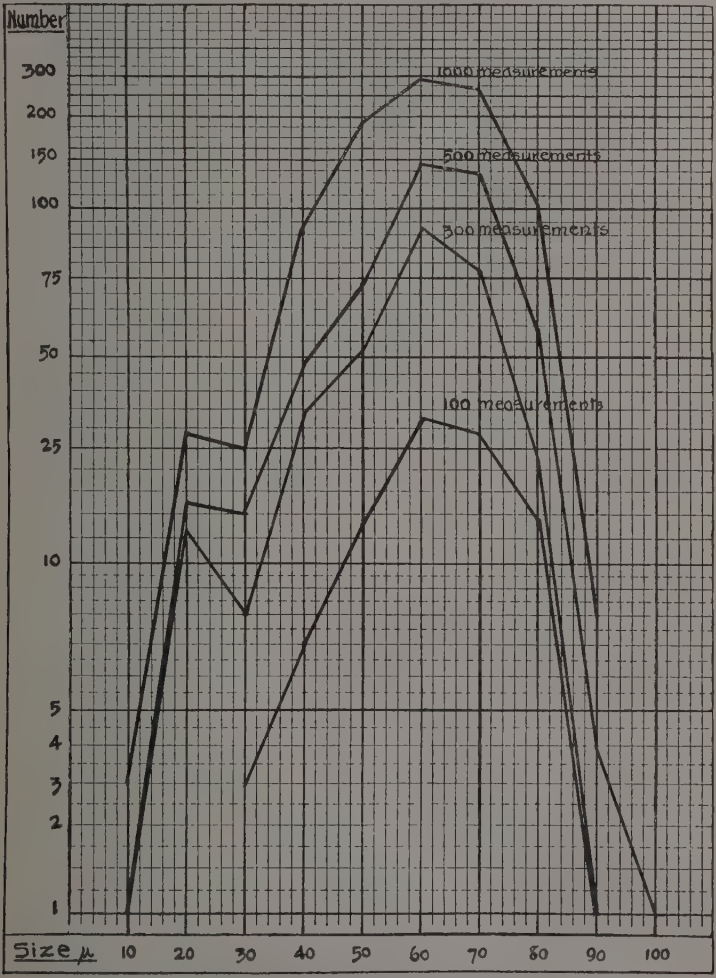

Fig. 1. Types of Curves Obtained from Measuring the Length of 100, 300, 500, and 1000 Spores of *Helminthosporium sativum* Produced on Potato Dextrose Agar at 32° C.

a normal one. In general contour the 300-spore curve and the 500-spore curve approach the 1000-spore curve, altho the first is somewhat more irregular. The slight rise at the lower extreme indicates that the short spores tend to group themselves about a mode of their own. It is possible that improvement in the method of sampling might increase the accuracy of the results obtained from a smaller population. In the present study about 100 spores were measured from one mount. The spores were distributed as evenly as possible in the drop of water and each spore was measured in passing systematically over the slide from the upper left to the lower right hand corner. An attempt was made to make the mount so that two or three spores would come into the field at once. For all other conditions, 500 spores were measured.

Results obtained in the study of the morphology of spores developed on potato dextrose agar at various temperatures are interesting. Table III shows very little difference in the means of spores developed at 18° and 24°. From the comparisons in Table IV it is seen that these differences are insignificant. If, however, we examine the coefficients of variability, we find that there is a significant difference in the amount of relative variation in the length of spores. This fact is very clearly brought out in the curves in Figure 2. The degree of variation is not increased by a temperature 4 degrees lower (14° C.), but the mean length of the spores is slightly increased. This may be due to the fact that at a lower temperature the black outer wall on the spores and mycelium is laid down much more slowly, so that the spores have a longer time in which to form. This is further substantiated by the fact that at 32° the spores are very much shorter. The amount of relative variation is practically the same as at the lower extreme. These differences in length of spores produced at various temperatures are graphically represented by the curves in Figure 2.

The most striking difference in spore morphology was obtained by comparing the spores produced on different media. As the fresh leaf and the autoclaved head cultures were incubated at 24° C, we may compare these results with those obtained from the agar culture at 24° C. Comparing first the spores from the head and from the agar, we find that the former are slightly longer. The amount of relative variation in the two is practically the same. On the fresh leaves, however, the spores are very much longer and decidedly more uniform. These differences are illustrated in the curves in Figure 3.

TABLE III

VARIATIONS AND CONSTANTS FOR LENGTH OF SPORES OF *Helminthosporium sativum* PRODUCED UNDER DIFFERENT CONDITIONS

Conditions under which spores were produced		Distribution in classes (microns)												No. of spores measured	Extremes	Mode	Mean	Standard deviation	Coefficient of variability
Temperature, degrees C.	Medium	10	20	30	40	50	60	70	80	90	100	110	120						
14	Potato dextrose		4	25	36	48	85	138	99	38	10	15	2	500	24.5-119.0	70	67.32 ±0.55	18.41 ±0.39	27.30 ±0.62
18	Potato dextrose	1	21	22	22	38	93	147	131	22	2	1		500	14.0-105.0	70	65.02 ±0.52	17.23 ±0.37	26.50 ±0.60
24	Potato dextrose	1	4	8	17	50	107	217	88	8				500	14.0- 87.5	70	65.75 ±0.37	12.28 ±0.26	18.68 ±0.41
28	Potato dextrose		11	14	48	127	197	98	5					500	17.5- 80.5	60	55.98 ±0.35	11.47 ±0.24	20.49 ±0.46
32	Potato dextrose	1	16	15	48	73	149	136	57	4	1			500	14.0- 98.0	60	59.66 ±0.45	14.81 ±0.31	24.82 ±0.56
24	Sterile barley head	1	5	7	14	33	100	203	122	13	2			500	14.0- 98.0	70	67.74 ±0.38	12.63 ±0.27	18.64 ±0.40
24	Fresh barley leaves					3	8	89	117	180	39	3	1	500	49.0-115.5	90	83.14 ±0.29	9.77 ±0.21	11.15 ±0.24

TABLE IV

Summary of Comparisons Between Means and Coefficients of Variability for Length of Spores of *Helminthosporium sativum* Produced Under Different Conditions From Data Summarized in Table III.

Conditions compared	Means		Coefficients of variability	
	Difference	Difference divided by the probable error of the difference	Difference	Difference divided by the probable error of the difference
14° C. and 18° C.	2.30±0.75	3	0.80±0.86	1
14° C. and 24° C.	1.57±0.66	2	8.62±0.74	12
14° C. and 28° C.	11.34±0.65	17	6.81±0.77	9
14° C. and 32° C.	7.66±0.71	11	2.48±0.83	3
18° C. and 24° C.	0.73±0.64	1	7.82±0.73	11
18° C. and 28° C.	9.04±0.63	14	6.01±0.76	8
18° C. and 32° C.	5.36±0.68	8	1.68±0.82	2
24° C. and 28° C.	9.77±0.51	19	1.81±0.62	3
24° C. and 32° C.	6.09±0.58	11	6.14±0.69	9
28° C. and 32° C	6.32±0.56	11	7.44±0.73	10
Head and leaves	15.40±0.47	33	7.49±0.47	16
Head and agar 24° C.	1.99±0.53	4	0.04±0.57	0
Leaves and agar 24° C.	17.39±0.47	37	7.53±0.48	16
Leaves and agar 28° C.	27.16±0.45	60	9.34±0.52	18

These facts show that in a single spore strain of a *Helminthosporium* of this type, marked variations may be found in the length of spores developed under various conditions. Differences in spore measurements by various authors are therefore to be expected, and very fine specific or varietal differences can not be drawn on the basis of spore size unless a large number of carefully controlled comparative studies have been made. Seemingly, the original spore measurements given by Pammel, King and Bakke are rather large (105 to 130 microns). Stevens has come nearest to approaching this length with a maximum of 122 microns. The same author states that the majority of his spores fall within 80 to 90 microns. By examining Table III it will be seen that the majority of the spores developed upon fresh barley leaves in a moist atmosphere fall within the 80 and 90 classes, or within 75.0 to 94.9 microns. Out of 4000 spores measured, only 43 were longer than 100 microns. On the fresh leaves the longest spore measured was only 115.5 microns. However, the optimum conditions for maximum and minimum spore length have not necessarily been obtained in these studies. On the basis of spore shape and similarity with the organism obtained from typical spot blotch lesions and the ability to produce spot blotch symptoms on barley, the organism undoubtedly should be included in the species *Helminthosporium sativum* P.K.B.

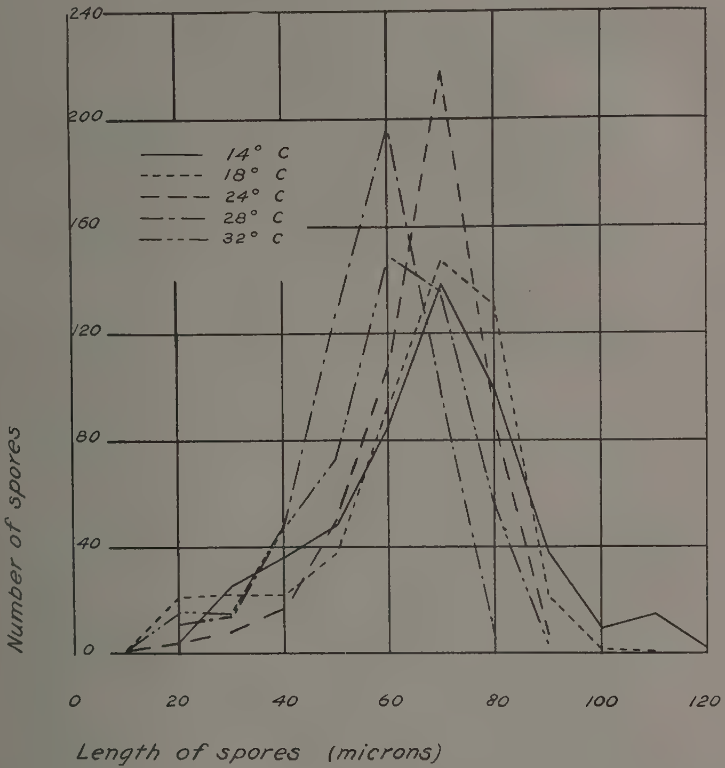

Fig. 2. Length of Spores of *Helminthosporium sativum* Produced on Potato Dextrose Agar at Various Temperatures

The shape of the spores was found to be more or less the same under various conditions. At 24° and 28°, the spores tended to be fat, spindle-shaped to broadly elliptical, sometimes slightly curved. At 32° the thickening in the middle was less evident, and they tended to be more uniform in diameter. The small spores were globose to ovate. At 14° the longest spores were mostly narrowly cylindrical. There was a marked tendency for the thickened portion to occur nearer the base than the apex, giving the spore the shape of a slender flask.

Throughout the culture work, bizarre forms frequently appeared, especially forked spores which were sometimes almost stellate. Seven or eight such single spores were isolated and planted on agar slants. In each case normal spores were produced and the bizarre type occurred so rarely that it was quite impossible to isolate another single spore of the same shape from the progeny.

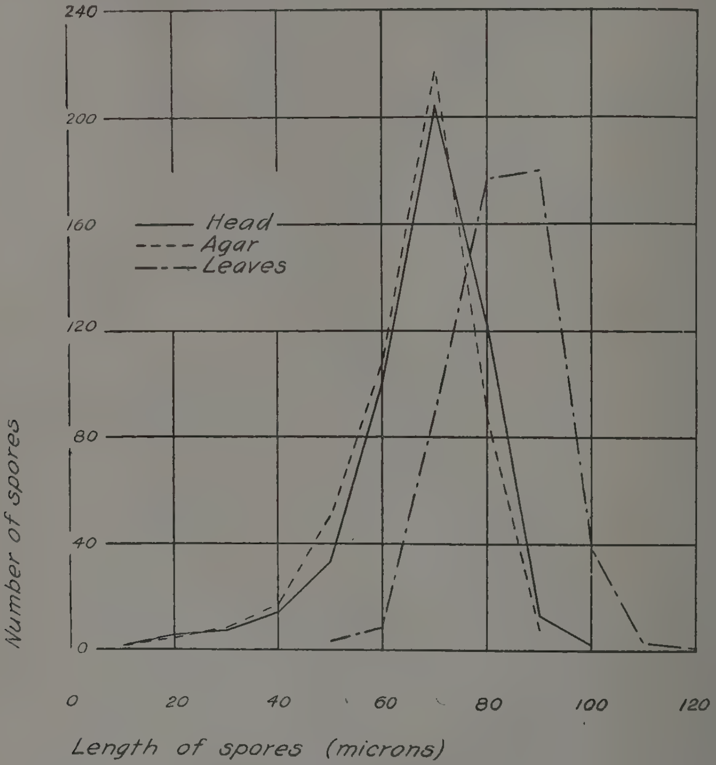

Fig. 3. Length of Spores of *Helminthosporium sativum* Produced on Different Substrata at 24° C.

The solid line represents spores produced on autoclaved ripe barley heads; the line with short dashes, spores produced on potato dextrose agar; the line with alternate long and short dashes, spores produced on fresh barley leaves in a moist chamber.

TEMPERATURE RELATIONS

GROWTH OF FUNGUS ON POTATO DEXTROSE AGAR

In determining the temperature relations of *H. sativum,* the first problem studied was the growth of the fungus in pure culture. In all, four series were run to determine the range of growth, the same general method being used in each. Thirty cubic centimeters of potato dextrose agar were poured into petri dishes 10 centimeters in diameter.

The plates were inoculated in the center and incubated at the various temperatures. Each series was run in triplicate. The diameter of the colony was taken as the index of growth. In some cases it was impossible to control the temperature within several degrees, so that one series can not be checked quantitatively against the other. Different lots of potato dextrose also were used in the different series. The results of two series are given in Table V. In each case, the size of the colony represents the average of three plates.

TABLE V

Effect of Temperature on Growth of *Helminthosporium sativum* on Potato Dextrose Agar

First Series (Feb. 28–March 3, 1921)		Second Series (Dec. 15–22, 1921)	
Temperature, degrees C.	Diameter of colony (after 9 days)	Temperature, degrees C.	Diameter of colony (after 7 days)
	mm.		mm.
0– 2	4	3– 6	9
6– 8	14	12–13	18
13–15	28	15–18	30
17–22	42	20–23	77
21–24	51	27–28	89
30–32	36	31–33	35
34–35	13	35–39	4
40–42	0	.....	..

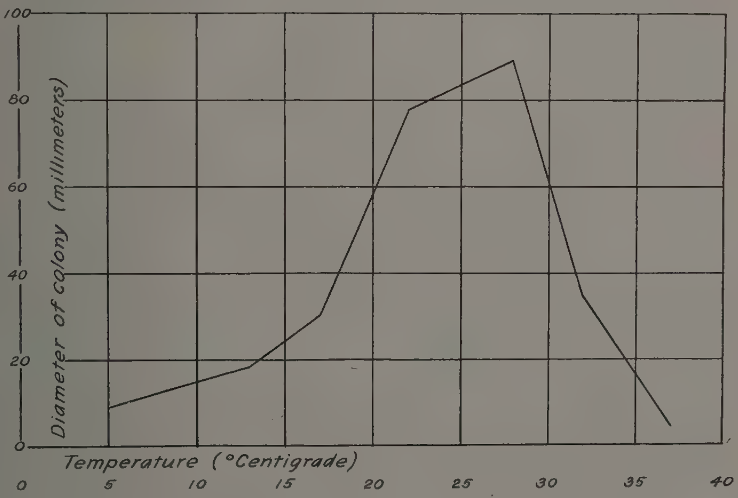

Fig. 4. Growth of *Helminthosporium sativum* on Potato Dextrose Agar in Petri Dishes The curve represents the diameter of the colonies at the end of seven days.

Data obtained in the second series are shown graphically in the curves of Figures 4 and 5. Figure 4 shows the relative growth of the fungus at the various temperatures after seven days. Figure 5 shows the daily rate of growth at each of the temperatures tested. Plate I shows the final appearance of the colonies in the first series, Plate II in the second.

From these results we may conclude that the minimum temperature for the growth of *Helminthosporium sativum* lies near 0-2° C., the maximum temperature between 35° and 39° C. and the optimum between 24° and 28° C.

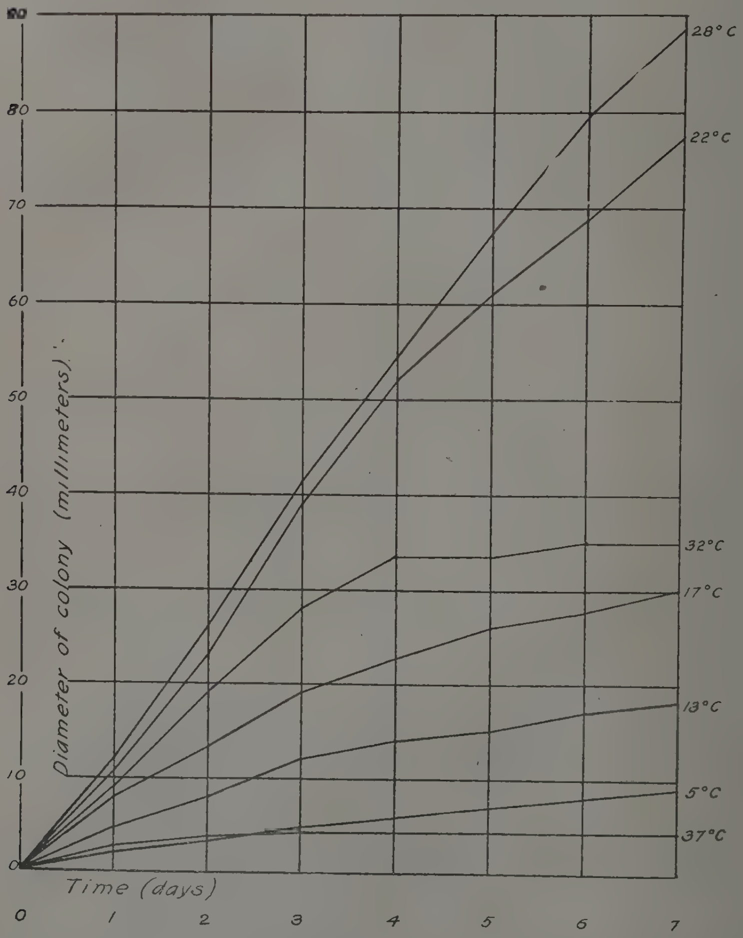

Fig. 5. Daily Rate of Growth of *Helminthosporium sativum* on Potato Dextrose Agar in Petri Dishes

SPORE GERMINATION

In the first series of studies to determine the effect of temperature on spore germination, hanging drop cultures were made on the covers of petri dishes, using distilled water and Czapek's solution, minus the sugar, as media. The spores were taken from a six-days-old bean agar culture. Germination counts were made after 48 hours. The results are given in Table VI.

TABLE VI

Spore Germination of *H. sativum* in Distilled Water and in Czapek's Solution at Various Temperatures

Temperature, degrees C.	Distilled water PH 6.7					Czapek's solution—sugar PH 6.0				
	1st drop	2nd drop	3rd drop	4th drop	Av.	1st drop	2nd drop	3rd drop	4th drop	Av.
	%	%	%	%	%	%	%	%	%	%
1	1—	1—	1—	1—	1—	20	10	15	10	14
6	10	8	20		13	30	50	40	50	42
14	10	20			15	55	50	62	40	52
18	40	40	30		37	66		50	60	59
24	68	41	44		58	85	86	75	75	80
30	45	65	48	41	50	77	70	59	80	72
34	50	60			55	36	50	25	42	38
42	0	0	0	0	0	0	0	0	0	0

With the exception of the results obtained at 34° C., a higher percentage of germination was obtained in Czapek's solution than in distilled water. In both cases the optimum occurred at 24°. At a temperature of 1° C. 14 per cent of the spores germinated in Czapek's solution, while less than 1 per cent germinated in distilled water. At 42° no germination occurred in either case, while at 34° the germination in distilled water was practically the same as at 30°, but in Czapek's solution a marked inhibition occurred at the higher temperature.

After trying various methods for germinating spores, including hanging drops in petri dishes, in van Tieghem cells, films on slides in moist chambers and in moist atmosphere, the most satisfactory method proved to be floating the spores on the surface of a thin layer of a liquid medium in Syracuse watch glasses. In such cultures the spores can be counted directly on the surface under the low power of the microscope.

In several series, through the different temperature ranges, consistently high percentages of germination were obtained at the extreme temperatures when water which had been redistilled over glass was used. Fluctuations occurred in the different cups at any one temperature. The results given in Table VII are typical. The percentages given in the table represent the average of several counts.

TABLE VII

Spore Germination of *H. sativum* in Redistilled Water at Various Temperatures

Temperature, degrees C.	Average percentage of germination	
	Spores floating on surface of water	Spores lying on bottom of cup
5.5– 6.5	87	76
11.5–12.0	93	89
17.0–19.0	73	57
21.0–24.0	62	61
28.0–29.5	70	66
30.5–32.0	83	46
34.0–35.0	65	63
38.0–39.0		65

In a second series, using hanging drops in petri dishes, 67 per cent of the spores germinated at 6°, 54 per cent at 12°, 79 per cent at 18°, 91 per cent at 22°, 72 per cent at 28°, 91 per cent at 29-30°, 80 per cent at 32°, 82 per cent at 35°, and 87 per cent at 39°.

In a third and fourth series in watch crystals, the spores were not counted but the germination was indicated as poor, moderate, and good. After 24 hours incubation, in these series, the germination was poor at 6°, moderate to good at 12°, 18°, and 22°, and good at the higher temperatures. By count, 89 per cent of the spores germinated at 39°. At the end of 48 hours the germination was good at 6°.

From these results with redistilled water it is difficult to detect any quantitative effect of temperature on the number of spores which germinate. Even at 1° C. a small number of spores will germinate. This, however, is probably very near the lower limit. At the lower temperatures, 1°, 6°, and 12°, pieces of mycelium in the cultures always germinated much more readily and sent out longer tubes than did the spores. At 40-42° no germination occurred in the first series for which the results are given. In later series, however, high germination sometimes occurred at 38-39°. Comparing these results with the data presented in Table V, we find 35-39° to be the maximum temperature for the growth of the mycelium on potato dextrose. At temperatures as high as 35° and 39° the germ tubes appeared very quickly, but were always short and did not increase much in length after two or three days. On the other hand, at 22°, 28°, and 32°, the tubes formed such a mat of mycelium by the end of 24 hours that it was often difficult to determine the percentage of germination. At the lower temperatures a longer time was required for the germ tubes to appear, and they increased in length very slowly.

In redistilled water, therefore, spores of *H. sativum* germinate about equally well at temperatures from 6° to 39° C. No very definite optimum temperature for germination is apparent. The character of the germ tubes and the length of time in which they appear, however, would indicate that an optimum temperature lies between 22° C. and 32° C. From these results it would seem that for the above-ground parts of the host, temperature is not a limiting factor in infection so far as spore germination is concerned.

From the data in Table VII it will be seen that in most cases the percentage of germination of the submerged spores is only slightly less than that of those on the surface. In all cases, however, the germ tubes produced under water were very short and abnormally branched in comparison with the long straight tubes produced on the surface.

The germ tube first appears as a hyaline tip at the apex of the spore. It is difficult to determine whether the tube breaks through the wall or emerges through a pore. After the tube has increased in size, the delicate exospore is split, sometimes for a third of the length of the spore. A second tube soon appears at the base of the spore, just to one side of the scar where the spore was attached to the sporophore. The connection between the two tubes is continuous through the spore, showing the false nature of the septation in the endospore. The endospore is frequently drawn away from the exospore and forms a constricted tube through the latter. Two germ tubes are not always formed from each spore. In one lot of spores germinated in redistilled water at 22° C., it was found that 52 per cent of the spores possessed germ tubes at both ends and 39 per cent at only one end. Nine per cent of the spores did not germinate. Very rarely lateral tubes are found. One spore was observed with a lateral germ tube from each of five adjacent cells at one end of a ten-celled spore. In a few other cases, one or two lateral tubes were observed, usually arising from central cells. Fusions between germ tubes are very common.

EFFECT OF HYDROGEN-ION CONCENTRATION AND TEMPERATURE ON SPORE GERMINATION

As so many spores always germinated in redistilled water at the various temperatures which permitted germination at all, the effect of hydrogen-ion concentration on germination was studied. Culture solutions, based on Clark and Lub's (4) titration curve for ortho-phosphoric acid, were made by adding varying quantities of n/5 KOH to 50 cc.

n/5 H_3PO_4 to give a series of hydrogen-ion concentrations ranging from pH 2.4 to pH 12. The pH value of the solutions was determined colorimetrically, except for the highest three alkaline solutions for which the theoretical value according to the curve is given. Spores from a seven-weeks-old barley head culture were dusted over the surface of the solutions in Syracuse watch glasses. The percentage of germination was determined after 18 hours and after 36 hours. Similar series were run in triplicate at 19°, 24°, and 32° C. The results are given in Table VIII.

TABLE VIII

Spore Germination of *H. sativum* in H_3PO_4—KOH Solutions of Various Hydrogen-ion Concentrations at Different Temperatures

pH	Hours	Germination											
		19° C.				24° C.				32° C.			
		1	2	3	Av.	1	2	3	Av.	1	2	3	Av.
		%	%	%	%	%	%	%	%	%	%	%	%
2.4	18	0	0	0	0	0	0	0	0	0	0	0	0
	36	3	4	1	3	0	0	0	0	0	2	0	1
3.4	18	2	0	4	2	5	6	0	4	8	10	10	9
	36	2	4	7	4	4	0	2	2	10	13	7	10
4.4	18	15	17	14	15	40	36	28	35	44	44	28	39
	36	22	19	14	18	41	33	16	30	31	53	27	38
5.2	18	27	28	25	27	55	38	46	46	40	42	54	44
	36	28	33	25	29	52	39	52	48	44	41	52	44
6.4	18	31	25	40	33	50	59	57	55	47	76	52	44
	36	32	33	34	33	56	64	62	61	41	66	55	54
7.0	18	40	42	60	47	71	71	79	74	86	76	72	76
	36	36	45	53	45	68	65	84	72	65	74	60	66
7.4	18	30	39	68	46	81	75	72	76	78	80	84	81
	36	34	60	67	54	85	83	73	80	72	83	87	81
7.8	18	55	35	36	42	83	78	80	80	88	90	94	91
	36	30	34	35	33	83	90	90	88	97	94	92	94
8.0	18	35	24	29	29	72	62	68	67	72	65	74	70
	36	35	22	38	32	76	68	82	75	75	79	78	77
8.2	18	21	18	18	19	60	43	50	51	70	80	90	80
	36	19	24	19	21	72	61	65	66	75	85	84	81
9.2	18	25	40	34	33	62	58	63	61	87	82	87	84
	36	36	47	35	39	85	70	60	72	89	90	95	91
11.4*	18	22	22	20	21	33	40	32	35	84	83	82	83
	36	40	35	36	37	73	74	82	76	86	93	90	89
11.8*	18	12	18	12	14	0	0	8	3	40	26	39	35
	36	26	34	37	32	10	0	20	10	30	69	48	39
12.0*	18	0	0	1	0	0	0	0	0	0	1	0	0
	36	2	14	1	6	0	22	0	7	9	35	0	15

* Theoretical value according to Clark and Lub's titration curve for ortho-phosphoric acid.

After an incubation of 18 hours at 19° C. no germination was obtained at a hydrogen-ion concentration of pH 2.4. Very slight germination occurred at pH 3.4; while at pH 4.4 the germination showed a marked increase, rising steadily until a hydrogen-ion concentration of pH 7 was reached. From this point a gradual decrease occurred, reaching the lowest point at pH 8.2. At pH 9.2 there was a second rise followed by a gradual falling off, until at pH 12 no germination occurred. After incubating for 18 hours longer there was scarcely any change in the amount of germination on the acid side. There was a slight increase on the alkaline side.

At the higher temperatures the results were very much the same except that the percentage of germination was increased and the point of maximum germination was shifted slightly to the alkaline side. At both 24° and 32° the optimum germination occurred on the alkaline side of neutrality at a hydrogen-ion concentration of pH 7.8. A much greater increase in germination occurred at the higher temperatures on the alkaline side than on the acid. The average germination after 18 hours incubation at the different temperatures is represented by the curves in Figure 6.

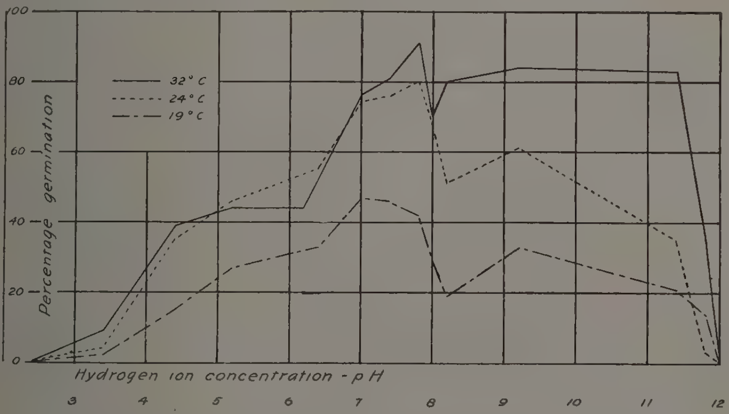

Fig. 6. Percentage Germination of Spores of *Helminthosporium sativum* in Phosphoric Acid—Potassium Hydroxide Solutions of Various Hydrogen-Ion Concentrations

Webb (14) germinated spores of *Aspergillus niger, Penicillium cyclopium, Fusarium sp., Botrytis cinerea,* and *Lenzites saepiaria* in n/5 mannite solutions in which the hydrogen-ion concentrations were adjusted by the use of $H_3 PO_4$ and NaOH according to Clark and Lub's titration curve for ortho-phosphoric acid. The results obtained with *Fusarium sp.* are the only ones comparable with those obtained with *H. sativum* in the wideness of the range of hydrogen-ion concentration which permits spore germination. It may be pointed out that both *Fusarium* and *Helminthosporium* are chiefly soil organisms. Among the organisms that Webb studied, only *Fusarium* responded favorably to an alkaline medium. Maximum germination occurred at hydrogen-ion concentrations of pH 2.8 and pH 7.4. From pH 6.2 a steady increase in germination occurred with the increase in hydrogen-ion concentration up to pH 2.8. From the same point, a steady increase in germination also occurred with the decrease in hydrogen-ion concentration and practically the same maximum was reached at a concentation of pH 7.4. Examining the data of *H. sativum* again, there is a steady decrease in germination from the neutral point with the increase in hydrogen ions up to a concentration of pH 2.4, where no germination occurred during 18 hours and only very slight germination during 36 hours. However, the usual bimodal curve is obtained, but, in this case, both maxima occur on the alkaline side at hydrogen-ion concentrations of pH 7.8 and pH 9.2. With *H. sativum,* germination occurred chiefly in the alkaline solutions.

A series of spore germination tests was also made in Czapek's solution minus the sugar, with various hydrogen-ion concentrations ranging from pH 2.6 to pH 9.8. The results are represented by the curve in Figure 7. In this case also the bimodal curve was obtained. The first maximum, however, occurred on the acid side of neutrality at a hydrogen-ion concentration of pH 6. The second was on the alkaline side at a concentration of pH 8.

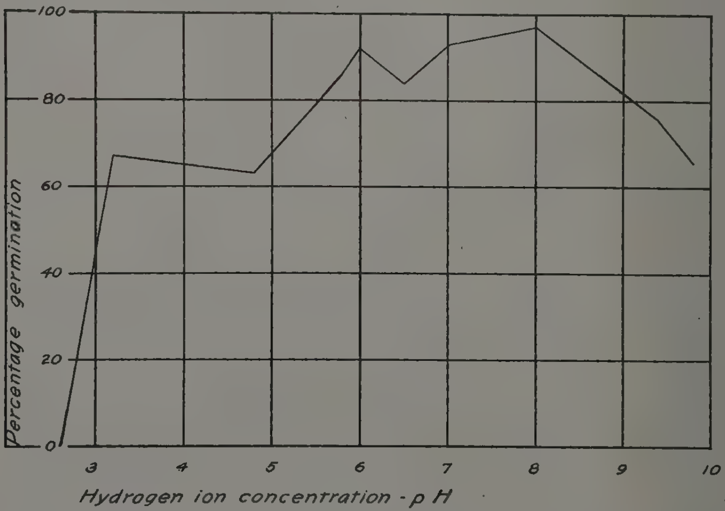

Fig. 7. Percentage Germination of Spores of *Helminthosporium sativum* in Czapek's Solution Minus the Sugar at Various Hydrogen-Ion Concentrations

While the germination of *H. sativum* spores in these solutions is not necessarily the same as in a soil solution, certain general relationships may be pointed out. The spores will germinate through a wide range of hydrogen-ion concentration. Optimum germination occurs near the neutral point or on the alkaline side. The spores will tolerate high degrees of alkalinity. Germination studies in solutions more nearly approximating soil solutions are still desirable from the standpoint of a closer analysis of the development of the disease.

INFECTION

Marquis wheat and Lion barley were grown under sterile conditions in test tubes containing white sand. When the seedlings were about an inch high, the coleoptile was inoculated with a suspension of spores and incubated at various temperatures. At 22°, 25°, and 30° C. characteristic minute brown lesions were visible after 18 hours. At the end of five days no infection had occurred at 6° on the barley; very light infection was evident on the wheat. Light infection also occurred on both wheat and barley at 14° and 34°, and on wheat at 30°. Moderate to heavy infection occurred on both hosts at 22° and 25°, and also on the barley at 30°. In these cases, the typical basal browning characteristic of the seedling blight occurred. This was as far as it was possible to follow the disease under these conditions. The results indicate that infection will take place to some extent through a rather wide range of temperature from 6° to 34° C. but that for the severe development of the disease the range is narrower, probably 22° to 30°. To some extent moisture, as well as temperature, was the limiting factor at the extremes.

F. L. Stevens (13) reports that, "In an adaptation of the rag-doll seed tester, which allows the use of seedlings under aseptic conditions and variations of moisture and temperature as desired, inoculation by spores of *Helminthosporium* upon the uninjured sheath was followed within 24 hours by entrance of the mycelium into the host cells, and within 48 hours by a browned, diseased spot visible to the naked eye. Subsequently, when conditions favored, the mycelium invaded the innermost leaves and caused general rotting and death. When inoculated upon the roots, there was general invasion of the cortex with very slight discoloration." Stevens does not report under what conditions of temperature and moisture the disease developed best.

An attempt was made to arrive at the temperature relations governing leaf infection by inoculating fresh excised leaves with spores of *H. sativum,* placing them in moist chambers and incubating them at various temperatures. After incubating for 72 hours at 6° C., both inoculated and uninoculated check leaves were dark green, turgid, and normal in appearance. No signs of infection were apparent. Microscopic examination showed that many spores had germinated but so far as could be detected from free hand sections, the germ tubes had not penetrated. After the same incubation period, at 12° C., very small blue-green water-soaked areas were visible at the points of inoculation. The remainder of the leaf tissue and the uninoculated check leaves were still green and normal in appearance. These water-soaked areas were not yet visible at the end of 48 hours' incubation. At 18° C., by the end of the third day, there were green water-soaked areas on which conidiophores were beginning to appear on the inoculated leaves. The tissue of the leaves was still firm and the cells were turgid. While the infected areas retained a dark blue-green color, the rest of the leaf was yellow. The uninoculated check leaves were light green to yellow in color. After 72 hours' incubation at 23°, 27°, and 30° C., there were large dark green blotches of infected tissue covered by a velvety mass of conidiophores. The leaf tissue was beginning to soften and the check leaves and non-infected areas were yellow. In the infected areas the cells were beginning to disintegrate, but the chloroplasts were still green. At 34° C. small water-soaked areas, 3 or 4 mm. in diameter, were apparent after 36 hours' incubation. At this time the border was beginning to turn brown. By the third day, there were small, brown, definite leaf spots, similar to the normal lesions produced on leaves in the greenhouse and in the field. The remainder of the leaf tissue and the check leaves were yellow.

Under the conditions just described, there was always an abundance of moisture, so that the difference in reaction must have been due to the influence of temperature on host and fungus. During the first 36 hours the results were probably more or less comparable to results obtained in growing leaves attached to the plant; during the second 36 hours, at some temperatures at least, the relationship was probably saprophytic. The most that can be claimed for results obtained in this way is that they are only indicative of what may happen on growing plants.

The results obtained from these experiments would indicate that at temperatures of from 18° to 30° C., penetration into the leaf will take place about equally well in the presence of sufficient moisture. Below 24° the spots increase in size more slowly, above 24° more rapidly. At 12° a much longer incubation period is necessary for the development of water-soaked areas than at higher temperatures. At 6° no visible infection was obtained. At a temperature as high as 34°, on the other hand, the development of the spots and the browning of the host tissue occurred so rapidly that further development of the fungus was checked.

While no control experiments were made with soil or leaf infection on growing plants, results obtained in the greenhouse agreed in general with those obtained on the temperature relations of the fungus. When the average temperature was between 75° and 85° F., much better infection was obtained than when the average was lower. Better results were obtained on an inner bench over the steam pipes than on an outer bench next the outside wall on the west end of the house where it was always cool, and vigorous plants developed in spite of heavy soil inoculation.

These results also agree with those reported by McKinney (8). He says, "Controlled soil temperature experiments, conducted in the 'Wisconsin temperature tanks,' and field experiments show that seedling infection in both spring and winter wheat and in spring barley is greatest at relatively high temperatures. The optimum temperature apparently lies between 26° and 28° C. This is very near the optimum rate of growth of *H. sativum* in pure culture."

INFLUENCE OF TYPE OF SOIL

The statement has already been made that particularly severe infections of *Helminthosporium* foot- and root-rots were observed during the summer of 1920 on sandy soils and on peat soils in certain localities in Minnesota. Consequently one of the first tests undertaken was a study of the development of the disease in different types of inoculated soil in order to gain, if possible, an insight into the individual factors which might be influencing the situation.

A heavy loam, a sandy loam, a sand, and a peat soil were selected for use. The heavy loam was a black dirt used without modification; the sandy loam was obtained by mixing two parts of the heavy loam with one part of quartz sand; and the sandy soil by mixing one part of the heavy loam with two parts of coarse sand. All this soil was passed through a 5-millimeter mesh screen before being packed into the pots. The peat was a high-lime peat obtained from Anoka County through the Division of Soils, and fertilized according to directions with acid phosphate and potassium chloride to secure maximum yield from this particular type of soil (1).

Small pots of steam-sterilized soil were planted with Marquis wheat and Lion barley. After the seeds were planted, the soil was watered several times with a heavy suspension of *Helminthosporium* spores.

When the plants became crowded in the small pots, they were transplanted to larger pots containing sterilized soil which had been inoculated in the same way. In these pots, the plants were grown to maturity.

There was no very serious seedling blight in any of the pots. The coleoptiles of most of the plants were darkened, and lesions were formed on the first leaves. The seedlings in the inoculated soils were not noticably smaller than those in the uninoculated, sterilized, check soils. When about six weeks old the height of the plants was measured in order to determine the effect of the disease on growth. The results are given in Table IX. In each case the table gives the average height of 30 to 40 plants.

Any differences in height of the plants in the different soils in either the uninoculated or inoculated series may be considered due to the influence of the soil in which they grew. As will be seen from Table IX, the differences between the plants in the different types of soil in the inoculated series, altho small, agree fairly well with similar differences in the uninoculated series. The differences between check plants and inoculated plants in the same type of soil may be considered to be the result of the disease. A comparison of the differences between plants in inoculated and uninoculated soils of the different types will give an index of the influence of the soil type on the development of the disease.

TABLE IX

AVERAGE HEIGHT OF WHEAT AND BARLEY PLANTS GROWN IN INOCULATED AND UNINOCULATED SOILS OF VARIOUS TYPES

Type of soil	Marquis wheat		Lion barley	
	Inoculated	Check	Inoculated	Check
	cm.	cm.	cm.	cm.
Heavy loam	22.8	30.2	24.5	27.6
Sandy loam	21.0	32.3	29.0	31.1
Sand	23.0*	33.6*	25.3	28.3
Peat	29.4*	41.7*	29.4	33.6

* Plants were measured two days later than those in the heavy loam and in the sandy loam, and so can not be compared with these.

Judging by the height of the plants at this stage, the barley developed about equally well in the heavy loam and in the sand, the difference in the average height being 8 millimeters in the inoculated series and 7 millimeters in the check series. The increases over this amount were about equal in the sandy loam and in the peat, the advantage being slightly in favor of the latter. The difference between the height of plants in inoculated and uninoculated soils was practically the same in the heavy loam and in the sand. This would indicate that these two types of soil had practically an equal influence on the development of the disease.

The difference was less pronounced in the sandy loam, showing that here the disease had least influence on the size of the plants. The greatest difference in height was in the peat soil, indicating that here the disease had most influence on the growth of the plant. From these results it is apparent that root-rot of barley produced the greatest effect on the host in the peat, a less marked effect in the sand and heavy loam, and the least effect in the sandy loam. On the whole, the differences were very small. The further development of the disease on the barley plants was not followed.

The conclusions to be drawn from the height of the wheat plants at this stage must be derived from comparisons between the differences in the height of diseased and check plants in the same type of soil. It is obvious that the effect of the disease is much more marked on the wheat than on the barley. The least effect of the disease on the growth of the plants was obtained in the heavy loam. There was practically an equal increase in effect in the other three types of soil.

The wheat was then transplanted to larger pots of inoculated soil. In each case, the most severely diseased plants were transferred. After transplanting, the check plants grew much faster than the diseased plants, and headed several days earlier. Plate III shows the comparative vigor and size of the plants in the different types of soil at maturity. Final observations were made on the Marquis wheat just before the heads began to turn yellow. The plants were removed from the soil, carefully washed, and examined for foot- and root-rot.

In the heavy loam soil, both diseased and check plants averaged 3.5 culms per plant. While the severity of infection, measured by the degree of browning at the base of the plant, was moderate, there was very little difference in the extent of the root systems. The check plants headed four days earlier than the diseased plants and were considerably more vigorous. A slight browning occurred at the base of most of the mature check plants which resembled slightly a light infection by *Helminthosporium*. The lesions, however, were less definite and no organism was obtained from tissue cultures. *H. sativum* was isolated from the base of diseased plants.

In the sandy loam, the average number of culms on each diseased plant was 3, on each check plant 2.5. The basal infection was moderate. There was little difference in the root systems.

In sand the average number of culms on each diseased plant was 3, on each check plant 2. The infection at the base of the diseased plants ranged from moderate to heavy minus. The root systems of the diseased plants were considerably less extensive, brown lesions were numerous, and the roots were very easily broken. The contrast between diseased and check plants was greatest in this type of soil.

In the peat soil the average number of culms on inoculated plants was 2.7, on uninoculated 2.6. Basal infection was light to moderate. There was very little difference in general appearance of the plants grown in inoculated soil and in uninoculated soil. The best plants in both series were obtained in the peat soil.

Under the conditions studied, the root-rot inhibited the growth of Lion barley most, during the first six weeks, in the peat soil. The effect of the disease was less evident in the heavy loam and the sand, and least evident in the sandy loam. During the same period, the growth of Marquis wheat was least inhibited in the heavy loam. The effect of the disease on the growth of the plants was markedly increased, and to practically the same extent, in the other three types of soil. By the time of maturity, however, the disease had developed much more severely in the sand, as evidenced by the smaller size of the plants, their decreased vigor, the amount of basal browning, and the breaking down of the root system. The effect of the disease was almost as severe in the heavy loam. In both the sandy loam and the peat there was only a very slight difference between the plants grown in inoculated and uninoculated soil.

In analyzing the factors involved in these various soils, it may be pointed out that in the loam soils, in addition to the change in physical texture brought about by adding increasing quantities of sand to the original heavy loam, there has been a dilution of the mineral nutrients of the host, a decrease in the water-holding capacity, a decrease in the amount of organic matter in the soil, and an increase in the amount of soil aeration. All these factors may be assumed to have an influence on both the host and the pathogene. On the other hand, in the peat soil, we have a high organic content, a high water-holding capacity, and an optimum of mineral nutrients for the host. The abundant moisture and high organic content of the peat soil should seemingly be conducive to extensive saprophytic growth of *Helminthosporium,* thus greatly increasing the amount of inoculum and the chance for infection of the growing host. This tendency, however, seems to be counterbalanced by the optimum conditions offered for the growth of the host. On the other hand, the greater severity of the disease in sand and heavy loam suggests a possible influence of the soil water. These results led to a further study of the influence of the soil moisture and of soil fertility on the development of the disease.

INFLUENCE OF SOIL MOISTURE

Preliminary series of experiments were carried out in the greenhouse in the following manner in order to determine the effect of soil moisture on the development of *H. sativum* on Lion barley. Light loam soil was sifted through a 5 millimeter screen, packed into jars, and sterilized. The sterilized soil was mixed with a culture of *H. sativum* grown on sterilized oats seed. Five degrees of soil moisture were maintained more or less uniformly by adding definite amounts of water each day. In the fifth series the soil was kept saturated by standing the porous pots in jars of water. In the other four series the soil was in glazed jars and the soil moisture was regulated by adding different amounts of water. Each moisture series was carried out in triplicate, in both inoculated and uninoculated soil. The seed was sterilized with silver nitrate before planting.

Comparative results on the infection above ground at the end of three weeks and below ground at the end of four weeks are summarized in Table X. In this table the infection is designated by fractions; the denominator represents the number of plants in one pot, the numerator the number that were infected. On examining the data, it is seen that, as far as the above ground parts of the plants are concerned, the percentage of infection, as well as the severity, is increased as the amount of soil moisture is increased. Comparatively few infections occurred on the check plants.

The relation of soil moisture to root infection is a little more difficult to see, as here the development of the roots in inoculated and uninoculated soils with the same moisture content must be compared, and then these differences compared for the various series. The roots were most severely rotted in the saturated inoculated soil, and the difference in the extent of the root systems of diseased and check plants was greatest here. The next greatest difference was in the first series, with a soil moisture content averaging 9 per cent, while the least difference was found in the third and fourth series. In these two series the plants grew best of all, in both the inoculated and uninoculated soils. Injury to the roots is brought about by rather limited local lesions which kill the root tips or cut off portions of the roots when the lesions occur back from the tips. Very often the roots are rotted off near the seed.

These results would indicate that plants suffer most from root infection by *H. sativum* in soils containing both maximum and minimum extremes of moisture. When conditions are more nearly favorable for the optimum growth of the plants, the effect of the disease can be overcome, and root systems are developed in inoculated soil almost equal in extent to those in clean soil.

TABLE X

Summary of Comparative Results on the Development of the *Helminthosporium* Foot-Rot on Lion Barley Under Varying Conditions of Soil Moisture

Series	Average soil moisture	Above ground infection (Three weeks after planting)		Soil infection (Four weeks after planting)	
		No. of plants	Notes	Foot-rot	Roots
I	9%	$\frac{3}{23}$	Brown spots on first leaves.	Moderate	Roots few, long and coarse, few secondary branches. Many brown lesions on the roots, especially near the seed and at the tips, but to some extent on all parts.
		$\frac{8}{17}$	3 seedlings killed, 1 with leaf spotted, remainder with lesions on the sheaths.		
		$\frac{2}{13}$	Light infections on first leaves and sheaths.		
II	13%	$\frac{7}{19}$	Light infection on sheaths and first leaves.	Moderate	Root system slightly better than in I. Roots coarse with few secondary branches. Lesions numerous. Difference between inoculated and check roots not so marked as in I.
		$\frac{12}{23}$	1 seedling killed, 1 with first leaf destroyed, moderate infections on remaining sheaths.		
		$\frac{22}{22}$	2 seedlings killed, moderate infections on remaining sheaths.		

TABLE X—*Continued*

Series	Average soil moisture	Above ground infection (Three weeks after planting)		Soil infection (Four weeks after planting)	
		No. of plants	Notes	Foot-rot	Roots
III	16%	$\frac{28}{28}$	1 seedling with severe infections on first and second leaves, stunted; remainder moderate.	Moderate minus	Tendency toward coarse roots without branches but not to such a marked extent as in I and II. Few but very severe lesions. Very little difference in extent of root systems of diseased and check plants. Best growth of plants in any of the inoculated series.
		$\frac{26}{26}$	1 seedling with first leaf killed, 1 with plumule killed.		
		$\frac{25}{25}$	1 seedling with first leaf killed.		
IV	25%	$\frac{13}{21}$	1 seedling killed, 1 with first and second leaves killed.	Moderate	Roots relatively few and very coarse. Most of them killed at tips.
		$\frac{11}{18}$	1 seedling killed, one with first leaf killed.		
		$\frac{16}{28}$	1 seedling with first and second leaves killed, 1 with first leaf killed.		

TABLE X—*Continued*

Series	Average soil moisture	Above ground infection (Three weeks after planting)		Soil infection (Four weeks after planting)	
		No. of plants	Notes	Foot-rot	Roots
V	Mud	$\frac{8}{8}$	1 seedling killed.	Heavy	On 50% of the plants the roots were completely rotted off. Roots were very few in number and very coarse. Many severe lesions. Marked difference between diseased and check plants in extent of root systems.
		$\frac{17}{17}$	12 seedlings killed.		
		$\frac{18}{18}$	10 seedlings killed.		
I Check	9%	$\frac{2}{24}$	Small lesions on sheaths.	Light $\frac{2}{15}$	Root systems almost twice as extensive as in corresponding inoculated series. Main roots much finer with many secondary branches. No lesions.
		$\frac{0}{18}$			
		$\frac{0}{17}$			
II Check	15%	$\frac{3}{25}$	Small lesion on sheaths.	None	Not so many roots as in I check. Roots fine with many branches. No lesions.
		$\frac{5}{30}$	Small lesion on sheaths.		
		$\frac{2}{25}$	Small lesion on sheaths.		

TABLE X *Concluded*

Series	Average soil moisture	Above ground infection (Three weeks after planting)		Soil infection (Four weeks after planting)	
		No. of plants	Notes	Foot-rot	Roots
III Check	18%	$\frac{2}{26}$	First and second leaves killed.	Light $\frac{2}{15}$	Many roots, fine and branched. No lesions. Best growth of plants in any of the check series.
		$\frac{3}{27}$	Small lesions on sheaths.		
		$\frac{3}{25}$	1 seedling with plumule killed, 2 with small lesions on sheaths.		
IV Check	25%	$\frac{1}{17}$	Small lesions on sheaths.	None	Roots coarse with few secondary branches. No lesions. Marked difference between extent of root systems in check and diseased plants. Growth of plants good.
		$\frac{0}{17}$			
		$\frac{0}{15}$			
V Check	Mud			None	Comparatively few roots, coarse and with few secondary branches. No lesions. Growth of plants fair.

An attempt was made to check up the moisture relations of the disease under field conditions. In a series of six square-rod plots, three were planted to barley and three to wheat. The north half of the barley plots was planted with Manchuria and the south half with Lion; the north half of the wheat plots was planted with Marquis, the south with Bluestem. A field drill was used for planting. Several days before planting, the soil was inoculated by applying *H. sativum* grown on sterilized wheat seed. One half gallon of the culture was applied to each square rod. After the seed was planted, one of the barley plots and one of the wheat plots was sprinkled for ten minutes each morning and evening, a second of each was sprinkled for five minutes each morning and evening, and to the third no water was added. During the first part of the season, very little infection appeared on any of the plants except Lion barley. The weather was very cold during the first two weeks after seeding and scarcely any infection occurred. There was no seedling blight on the unwatered plot, very little on the moderately watered plot, and only a moderate amount on the heavily watered plot. Infection occurred mainly on the above-ground parts, resulting in leaf spots and lesions on the sheaths. Less than 1 per cent of the plants were killed. After the first two weeks, the amount of infection increased very rapidly on the heavily watered plot, so that at the end of six weeks 100 per cent of the plants were infected, and most of them were severely attacked. On the moderately watered plot about 80 per cent of the plants were infected, the severity of the infection ranging from light to moderate plus. On the unwatered plot, about 50 per cent of the plants were infected, the severity of the infection ranging from light to moderate.

The method of applying the water tended to keep a film of moisture on the lower, shaded leaves, forming almost a moist chamber near the surface of the soil. The sprinkling also offered a good opportunity for the spores to be splashed from the soil onto the leaves. During June, the weather was very hot. As a result of this combination of circumstances, the plants on the heavily watered plot were literally covered with *H. sativum* lesions. In many cases the plants were so badly infected at the base that they rotted off. This was not true to such a marked extent on the moderately watered plot owing, probably, to the fact that the surface of the soil was not kept wet enough to maintain a more or less constant layer of moisture just above the surface of the ground. The Manchuria barley was moderately affected, but the wheats only slightly.

Final data were taken just before the heads ripened. An attempt was made to obtain a quantitative estimate of the percentage of plants infected for the whole plot and an average of the degree of infection on the roots, foot, and node from individual plants. For this purpose, approximately equally large groups of plants were dug from the center, and also from each corner of the plots, two feet from the margins. Ten plants were taken from each group and for these fifty plants, the following data were recorded: the number of culms which headed; the number of tillers which did not head; the degree of infection—indicated as heavy, moderate, or light on the roots, foot, and nodes. Finally, the seed from each plot was weighed after threshing and the yield per acre was calculated from this. These data are summarized in Table XI. In order to obtain a simple mathematical expression for making comparisons, the percentage of heavy infections was multiplied by 10, the moderate by 5, and the light by 1, and the sum was taken as the index of the total infection. In order more easily to make comparisons, these sums were reduced to unity. Finally, these expressions for root and foot infections were totaled to obtain a means of comparing the combined foot- and root-rot with the relative amount of soil moisture and with the yield. For the sake of comparison these were also reduced to unity. In some cases the *Helminthosporium* infections were so complicated by *Fusarium* infections that it is quite impossible to say how much of the damage was due to each organism. This was especially true on the Manchuria barley. In general, the amount of injury was small. Altho the root-rot and the basal infection as measured by the degree of browning was sometimes heavy on a large number of plants, the plants were not noticeably stunted or immature as is often the case in severe cases of foot-rot. On the whole, there was more foot- and root-rot on the barley than on the wheat. The Lion barley alone shows an increase in the amount of foot-rot as the relative amount of soil moisture is increased. The differences are so small, however, that they can not have much significance. There were no indications of a correlation in yield with either the relative amount of soil moisture or the amount of foot- and root-rot. For both varieties of wheat, foot- and root-rot was slightly worse on the driest plot. In no case did the relative amount of soil moisture or infection influence the tillering of the plants.

TABLE XI

Summary of Data on Infection of Barley and Wheat by *H. sativum* Under Varying Degrees of Soil Moisture Under Field Conditions

Variety	Soil moisture	Culms Av. no. per plant		Infection													Yield per acre, bu.	Remarks
				Root				Foot				Node				Combined totals (root and foot)†		
		Mature	Immature	% H	% M	% L	Total*	% H	% M	% L	Total*	% H	% M	% L	Total*			
Lion barley	+++	1.8	.9	50	50	0	1.4	8	62	30	7.0	94	6	0	12.1	1.9	13.5	6% infected by Fusarium
Lion barley	++	1.6	.8	50	48	2	1.4	2	38	60	4.5	58	42	0	9.9	1.7	11.7	
Lion barley	+	1.8	.6	32	68	0	1.3	0	46	54	4.7	100	0	0	12.5	1.6	15.8	2% infected by Fusarium
Manchuria barley ..	+++	1.4	.4	74	26	0	1.7	0	58	42	5.5	24	58	18	6.9	2.0	22.9	10% infected by Fusarium
Manchuria barley ..	++	1.3	.4	81	18	0	1.7	0	34	52	3.7	43	45	12	8.3	1.9	14.6	36% infected by Fusarium
Manchuria barley ..	+	1.2	.3	88	12	0	1.8	0	45	55	4.7	61	34	5	9.8	2.0	25.0	26% infected by Fusarium
Marquis wheat	+++	1.2	.8	8	88	4	1.0	0	2	68	1.2	0	22	4	1.4	1.0	11.5‡	
Marquis wheat	++	1.1	.6	34	56	10	1.2	0	0	70	1.2	6	54	0	4.1	1.2	15.0	
Marquis wheat	+	1.0	1.0	40	60	0	1.3	0	20	70	2.8	18	48	0	5.3	1.4	17.2	
Bluestem wheat....	+++	1.1	.9	32	60	8	1.2	0	4	40	1.0	0	16	8	1.1	1.1	9.8‡	
Bluestem wheat....	++	1.0	.7	22	78	0	1.2	0	4	42	1.0	4	16	9	1.6	1.1	10.5	
Bluestem wheat....	+	1.0	.8	24	56	20	1.0	0	4	72	1.5	0	16	0	1.0	1.1	10.7	

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* These factors were arrived at in the following manner: the number of heavy infections was multiplied by 10, the moderate by 5, and the light by 1, the products were added and the summations in each column reduced to unity by dividing each by the smallest sum in the column.

† These factors were arrived at by combining the sums for root and foot infection and reducing these to unity.

‡ Stand poor, as many of the seeds were washed out during first few sprinklings.

Many factors that are difficult to control enter into field experiments and complicate the results in such a way as to make them indicative rather than conclusive. In these experiments foot- and root-rot developed slightly more vigorously on Lion barley in the wettest soil and on the two varieties of wheat in the driest soil. This may be only a confirmation of the earlier greenhouse experience that root infection tends to be worse under either extremely dry or extremely wet conditions.

INFLUENCE OF SOIL FERTILITY

The effect of soil fertilization on the development of foot- and root-rot caused by *H. sativum* was studied in field plots on Lion and Manchuria barley, and on Marquis and Bluestem wheat. Potassium and nitrogen in the form of muriate of potash and nitrate of soda were added to square-rod plots at the rate of 600 and 300 pounds of fertilizer to the acre. Treble superphosphate was added at the rate of 200 and 100 pounds. These fertilizers were so applied that there were plots with a heavy and a light application of each alone and in combination with a heavy and light application of each of the others, except that there were no combinations of nitrogen and potassium. In addition to these, complete fertilizer was applied at the rate of 600 and 300 pounds and manure at the rate of 20 tons and 10 tons per acre. Unfertilized plots were left as checks. All the plots were run in duplicate, one series planted with wheat and one with barley. The north half of the wheat plots was planted with Marquis, the south half with Bluestem, the north half of the barley plots with Lion, the south half with Manchuria.

Several days before planting, *H. sativum* grown on sterilized wheat seed was applied on the surface of the soil at the rate of one half gallon of the culture to the square rod. The plots were seeded with a field drill, wheat at the rate of 90 pounds to the acre, and barley at the rate of 86 pounds. This is the normal rate of seeding for this section of the country.

Practically no seedling blight developed on any of the plots. Leaf lesions and foot-rot first appeared on the barley during the second and third weeks, and soon after lesions developed also on the wheat.

There was considerable difference in the vigor and height of plants on the different plots in response to the different fertilizers. During the latter part of the season, there were differences in the amount of lodging on the various plots. Final data on the amount of foot- and root-rot were taken just previous to the ripening of the grain. In order to obtain an approximately quantitative expression for the amount of infection in each plot, 50 plants were selected from each half square rod, 10 from each corner, two feet in from the margins, and 10 from the center of the plot. For each of these plants the following data were recorded: the number of culms which developed heads; the number of tillers which did not mature; the degree of infection (designated as heavy, moderate, or light) on the roots, the foot, and the nodes. After harvesting, the weight of the straw and of the threshed grain was recorded, and from this the yield per acre was calculated. The infection of Lion barley was slightly more pronounced than on the other hosts. These data for Lion barley are summarized in Table XII.

In order to arrive at a simple factor which would express the total infection for the roots, the foot, and the nodes for a single plot and would also take into account the severity of infection as well as the percentage of plants infected, the number of heavy infections was multiplied by 10, the number of moderate infections by 5, and the number of light infections by 1, and the three products were summed. This was taken as an arbitrary index of the infection. In order to make comparison more simple, these summations were reduced to unity by dividing each by the lowest sum. This is the factor designated as total infection in Table XII. In order to compare the combined effect of root- and foot-rot, the summation for each was added and these sums in turn were reduced to unity.

In order to bring out the relation of infection to fertilizers and yields, the arbitrary indices of infection were grouped into three classes and the yields per acre into three classes, and the fertilizer plots were arranged according to their infection and yield in the various classes as shown in Table XIII. From this summary table it is quite clear that the amount of foot- and root-rot is not correlated with any particular fertilizer.

The disease did not appear in its severest form on any of the plots. Under the conditions of this experiment, there was no evidence of severe stunting of the plants or of excessive tillering.

COMPARISON OF SEVERAL ROOT-ROT CAUSING ORGANISMS

In order to obtain comparative results on the pathogenic effect of different soil organisms on Marquis wheat and Lion barley, a culture of *Helminthosporium* isolated from the foot-rot of wheat in Illinois by F. L. Stevens and a culture of *Fusarium culmorum* (W. Sm.) Saccardo isolated from scabby wheat, were compared with the *Helminthosporium sativum* isolated from barley foot-rot in Minnesota.

TABLE XII

EFFECT OF *H. sativum* ON LION BARLEY IN RELATION TO VARIOUS FERTILIZERS

Fertilizer, lbs. per acre			Culms, Av. no per plant		Infection												Combined totals (root and foot)†	Yield	
					Root				Foot				Node						
K	N	P	Mature	Immature	% H	% M	% L	Total*	% H	% M	% L	Total*	% H	% M	% L	Total*		Grain, bu. per acre	Straw, tons per acre
600	600	200	2.6	1.7	24	25	38	1.4	18	44	38	3.1	24	46	18	1.3	1.3	30.0	1.340
300	300	100	1.2	0.6	24	36	38	1.6	8	48	44	2.6	38	56	6	1.8	1.3	34.6	1.570
	600	200	2.1	0.5	26	72	2	2.2	54	46	0	5.5	42	52	6	1.8	2.2	28.3	1.520
	600	100	1.4	0.6	4	72	20	1.5	6	62	32	2.9	78	22	0	2.3	1.3	32.1	1.490
	600		2.6	0.8	12	56	28	1.5	38	62	0	4.9	80	20	0	2.4	1.8	32.5	1,580
	300	200	2.6	0.8	8	52	40	1.4	24	66	10	4.1	94	6	0	2.6	1.5	24.8	1.345
	300	100	1.3	0.8	16	52	32	1.6	18	50	30	3.3	72	28	0	2.3	1.5	35.8	1.800
	300		2.3	1.1	4	36	60	1.0	10	66	24	3.2	12	88	0	1.5	1.2	28.8	1.430
		200	2.6	0.7	6	34	66	1.1	12	54	32	3.0	64	30	6	2.1	1.2	22.3	1.265
		100	1.0	0.1	14	70	16	1.8	24	40	36	3.4	20	72	8	1.5	1.6	30.6	1.645
600		200	2.7	0.6	8	54	38	1.4	28	54	18	4.1	70	28	2	2.2	1.5	25.0	1.360
600		100	1.0	0.1	20	56	22	1.8	4	36	60	2.0	16	34	50	1.0	1.3	24.8	1.485
600			1.7	1.1	4	84	12	1.7	22	60	12	5.0	34	44	10	1.5	1.7	20.6	1.385
300		200	2.3	0.8	6	56	38	1.4	6	58	36	2.8	68	26	6	2.1	1.2	23.3	1.440
300		100	1.0	0.2	18	56	26	1.7	0	10	90	1.0	20	42	38	1.2	1.0	18.8	1.030
300			1.7	0.9	12	68	20	1.7	14	72	12	3.7	26	66	16	1.5	1.6	21.7	1.160
20 tons manure			2.4	1.0	0	48	48	1.0	26	48	22	3.7	30	60	0	1.6	1.3	30.0	1.365
10 tons manure			1.8	1.0	6	80	14	1.7	70	24	6	5.9	60	14	16	1.8	2.1	27.1	1.470
No fertilizer			1.9	1.2	10	64	26	1.6	26	60	12	4.1	86	8	4	2.4	1.6	19.4	1.135
No fertilizer			1.8	1.1	16	68	16	1.8	26	64	8	4.2	46	54	0	1.9	1.8	19.0	1.580

* These factors were arrived at in the following manner: The number of heavy infections was multiplied by 10, the moderate by 5, and the light by 1, the products were added and the summations in each column reduced to unity by dividing each summation by the smallest sum in the column.

† These factors were arrived at by combining the sums for root and foot infection and reducing these to unity.

These organisms were grown on sterilized wheat seed to obtain a large amount of inoculum. At the end of two months, the cultures were practically masses of mycelium and spores. These masses were passed through a meat grinder and the pulp was thoroly mixed with sterilized soil in which the wheat and barley were then planted. The observations on seedling injury at the end of twenty days are summarized in Table XIV.

TABLE XIII

Summary of Data in Table XII

Infection classes

Yield	1.0 to 1.3			1.4 to 1.8			1.9 to 2.2		
	K	N	P	K	N	P	K	N	P
18.0 to 23.9 Bu. per acre	300		100	600					
			200	300					
	300		200	No fertilizer					
				No fertilizer					
24 to 29.9 Bu. per acre	600		100		300	200		600	200
		300		600		200			
							10 tons manure		
30 to 35.9 Bu. per acre	20 tons manure								
	600	600	200		600				
		600	100						
	300	300	100		300	100			

The results on the Lion barley were very sharp. Unfortunately, rats molested some of the pots. In the barley series, however, only the check plants were injured. Three plants were left in each of the three pots. The comparative size of the plants grown in soil inoculated with the various organisms is very well shown by Plate IV.

The figures in Table XIV show that all three of the organisms caused a dwarfing of the barley, the two cultures of *Helminthosporium* to a much greater extent than the *Fusarium*. The Minnesota strain almost completely destroyed the plants. The effect of the three organisms on the root systems is shown by Plate V. The nature of the injury caused by severe infections of *Helminthosporium* is further illustrated by Plate VI, where eight seedlings showing various degrees of infection are shown beside a normal seedling of the same age grown in sterilized soil.

TABLE XIV

SEEDLING INJURY CAUSED BY *Fusarium culmorum*, AND TWO STRAINS OF *Helminthosporium sativum*

OBSERVATIONS MADE 20 DAYS AFTER PLANTING

Organism	Marquis wheat			Lion barley		
	No. plants*	Av. height†	Above-ground infection	No. plants	Av. height	Above-ground infection
Check, sterile soil	25	$\frac{19.8\text{cm.}}{10}$	Very small lesions on sheath of 7 seedlings.	9	$\frac{21.8\text{cm.}}{9}$	None
Fusarium culmorum	32	$\frac{18.5}{12}$	Slight browning of sheath on 11 seedlings.	38	$\frac{14.7}{13}$	4 seedlings killed, less than 2.5 cm. high; 5 seedlings badly dwarfed, first 3 leaves rose at nearly the same place just above soil line; 17 with dark brown sheaths; 12 without discoloration.
Helminthosporium sativum Illinois culture	17	$\frac{13.7}{13}$	Seedlings killed; 5 seedlings moderately brown at base.	50	$\frac{9.1}{17}$	7 seedlings with small lesions on leaves; 22 seedlings browned at base, infection varying from slight to severe.
Helminthosporium sativum Culture 82a	28	$\frac{9.9}{17}$	6 seedlings with leaf lesions; 7 seedlings darkened at base, injury very slight.	35	$\frac{4.1}{13}$	100% infection; 12 seedlings killed, less than 4 cm. high; 8 seedlings with first leaf killed; 2 seedlings with small lesions on first leaf; all severely browned at base.

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* Irregularity in the number of plants is due to the fact that some were destroyed by rats.

† Numerator denotes average height, denominator number of plants measured. Except for the uninoculated Lion barley, all the plants measured in each case were in one pot.

The results obtained with Marquis wheat are not so clear, as all the pots were molested more or less. The amount of injury caused by foot- and root-rot was very much less than on the barley. The Illinois strain of *Helminthosporium* seemed to cause slightly more injury than the Minnesota strain.

This series was started in the greenhouse during warm weather early in October when the temperature in the house was very high. The subsequent development of the disease was most interesting. After three weeks, the plants were thinned so that only three remained in each pot except for those inoculated with *H. sativum,* culture 82a, of which only three plants in each pot survived. These were badly stunted and infected at the time. The pots were kept next to the outer west wall of the greenhouse, where the temperature was always low during winter. The position of the pots was changed periodically so that all the plants would have more or less equal advantages as to sunlight. The plants grew remarkably well, and after a few weeks scarcely any differences could be detected between the different series. The barley stooled excessively and did not head well. The wheat was very good. At heading time, late in April, there was practically no difference between either the wheat or the barley plants grown in the clean soil and in the soil inoculated with the Minnesota strain of *H. sativum* or the *Fusarium culmorum.* The wheat in the soil inoculated with the Illinois strain of *Helminthosporium* was very bushy and developed only one or two heads per pot, while the other wheats developed from four to eight. The Lion barley was also slightly poorer in the soil inoculated with the Illinois strain than in the others. The barley did not head well, however, in any case.

Under the conditions of this experiment, then, the *Helminthosporium* caused more injury to Marquis wheat and Lion barley than the *Fusarium,* both in the seeding and the mature stages. While the Minnesota strain of *Helminthosporium* caused decidedly more seedling blight on the barley, the Illinois strain caused slightly more stunting of the mature plants. The Illinois strain caused more injury to the wheat at both stages.

SUMMARY AND CONCLUSIONS

In recent years a foot- and root-rot of wheat, rye, and barley has been serious in certain localities in Minnesota. A *Helminthosporium* of the *sativum* type has been constantly isolated from the diseased plants. In addition to causing a foot- and root-rot, the same type of organism attacks the leaves and stems and especially the nodes, glumes, and kernels of cereals and a large number of wild grasses. A strain of the organism was isolated from a foot-rot of barley. A pure culture was secured by isolating a single spore. The morphology of the organism was studied under various conditions with regard to its specific identity. The physiology and pathogenesis were studied with special reference to environmental conditions most favorable to the development of foot- and root-rot.

The organism is capable of causing disease symptoms similar to those described by Pammel, King and Bakke in 1910. Discrepancies are found between the spore measurements of this organism and that described by Pammel, King and Bakke, but since wide variations occurred under different conditions in a single-spore culture of the organism studied, the similarity of disease symptoms is considered sufficient justification for considering the organism to be *Helminthosporium sativum* P. K. B.

Variations in the morphology of the spores were found to occur under different conditions of growth. For spores as variable in length as those of *H. sativum,* it was found necessary to measure 500 spores in order to obtain accurate results.

On potato dextrose agar, significant differences in mean length of the spores occur when the organism is grown at different temperatures. The shortest spores with a mean length of 55.98±0.35 microns were produced at 28° C. The longest spores, with a mean length of 67.32±0.55 microns, were produced at 14° C. The difference between the two means is 14 times the probable error of the difference.

The greatest differences in length were found between spores produced on different substrata. At 24° C. the mean length of the spores produced on potato dextrose was 65.75±0.37 microns, on autoclaved ripe barley heads 67.74±0.38 microns, and on green barley leaves 83.14±0.29 microns. The difference between the means of the spores produced on the agar and on the leaves is 37 times as great as the probable error of the difference.

The temperature relations of the fungus were studied and it was found that the mycelium will grow at from 1° C. to 37° C., the optimum lying near 28°. The spores germinated in redistilled water about equally well at temperatures ranging from 6° to 39°, but the length of the germ tubes indicated that the optimum temperature is between 22° and 32°. Germ tubes penetrated the tissue of both the coleoptile and the leaf at from 12° to 34°, but severe infection occurred through a narrower range, from 22° to 30°, the disease developing faster at the higher temperatures. Above 30°, however, the development of the lesions seemed to be checked, altho they appeared very soon after inoculation. In general, we may say that rather high temperatures are most favorable to the growth of the fungus, to spore germination, to infection, and to the development of the disease.

In phosphoric acid–potassium hydroxide solutions, the spores germinated through a wide range of hydrogen-ion concentrations. A double optimum occurred, both maxima falling on the alkaline side of neutrality at pH 8.2 and pH 9.2. In Czapek's solution minus the sugar, the maximum germination occurred at pH 6 and pH 8. In general, the spores germinate better in alkaline solutions than in acid solutions. The spores will tolerate high degrees of alkalinity.

Leaf infection increases directly with the amount of moisture present. Greenhouse experiments indicate that the effects of root and foot infections are more severe in extremely dry and extremely wet soils than in soils containing an optimum amount of moisture for the growth of the host plant.

During one year's field experimentation, no correlation was found between the fertility of the soil and the development of foot- and root-rot.

The pathogenic effect of *H. sativum* isolated from barley plants in Minnesota was compared with that of a *Helminthosporium* isolated from stunted wheat in Illinois and with *Fusarium culmorum* isolated from scabby wheat. Experiments were made to determine the ability of these organisms to cause root- and foot-rot of Marquis wheat and Lion barley. Under the conditions of the experiment, the *Helminthosporiums* caused more injury than the *Fusarium*. The Minnesota strain of *Helminthosporium* caused the greater amount of seedling injury on the Lion barley, while the Illinois strain caused the greater dwarfing of the mature plants on both wheat and barley.

As a result of these studies, the wide-spread occurrence of *H. sativum* may be explained by the fact that the fungus responds saprophytically to such a wide range of environmental conditions. Neither the effect of temperature nor acidity seems to be a limiting factor in the development of the disease so far as spore germination is concerned. As a parasite, the fungus causes rather limited local infections. The amount of injury is determined largely by the number and size of the lesions. A direct correlation exists between the amount of moisture present and the number of lesions. The severity of the infection is greater at rather high temperatures than at low temperatures. The disease may be expected to develop most severely, therefore, at high temperatures in the presence of sufficient moisture.

Root and foot infections are more severe in certain soils than in others. This is probably largely due to differences in soil moisture and temperature. In general, the disease causes the greatest injury under conditions unfavorable to the growth of the host. Factors, such as soil fertility, which might then be expected to influence the disease, apparently have little effect.

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PLATE I

Helminthosporium sativum P. K. B. grown on potato dextrose agar at the following temperatures:

(1) 0° — 2°C., (2) 6° — 8°C., (3) 13° — 15°C.,
(4) 17° — 22°C., (5) 21° — 24°C., (6) 30° — 32°C.,
(7) 34° — 35°C., (8) 40° — 42°C.

Incubated 9 days.

PLATE II

Helminthosporium sativum P. K. B. grown on potato dextrose agar at the following temperatures:

(1) 3° — 6°C., (2) 12° — 13°C., (3) 15° — 18°C.,
(4) 20° — 23°C., (5) 27° — 28° C., (6) 31° — 33°C.

Incubated 7 days.

PLATE III

Marquis wheat showing the effect of *Helminthosporium* root-rot in the following types of soil:

A 1. Heavy loam, soil inoculated with *H. sativum* P.K.B.
A 1C. Heavy loam, uninoculated, sterilized soil
A 2. Sandy loam, soil inoculated with *H. sativum* P.K.B.
A 2C. Sandy loam, uninoculated, sterilized soil
A 3. Sand, soil inoculated with *H. sativum* P.K.B.
A 3C. Sand, uninoculated, sterilized soil.
A 4. Peat, soil inoculated with *H. sativum* P.K.B.
A 4C. Peat, uninoculated, sterilized soil.

PLATE IV

Lion barley plants, 3 weeks old, growing in soil inoculated with the following organisms:

1. *Helminthosporium sativum* P.K.B. Culture 82a, isolated from stunted barley plants in Minnesota
2. *Helminthosporium* isolated from stunted wheat plants in Illinois
3. *Fusarium culmorum* (W. Sm.) Saccardo
4. Uninoculated, sterilized soil

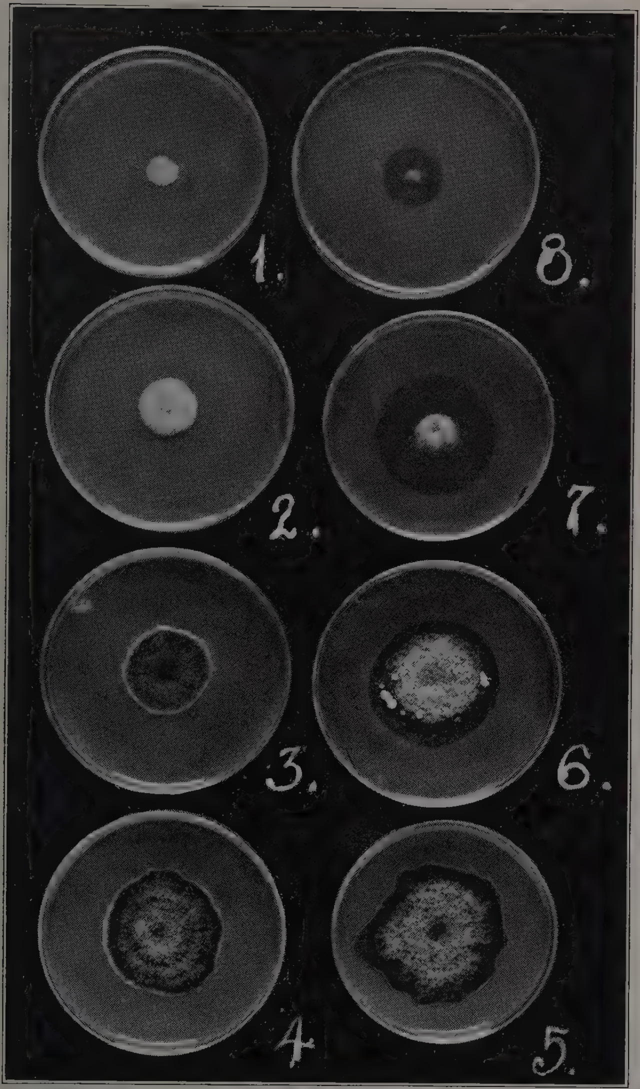
PLATE V

Lion barley plants, 3 weeks old, showing effect of the following soil organisms on development of root systems

1. *Helminthosporium sativum* P.K.B. Culture 82a
2. *Helminthosporium* from stunted wheat plants in Illinois
3. *Fusarium culmorum* (W. Sm.) Saccardo
4. Normal roots grown in uninoculated, sterilized soil

PLATE VI

Lion barley plants, 3½ weeks old, showing effect of root infection by *Helminthosporium sativum* P.K.B. The eight seedlings on the left were grown in inoculated soil, the one on the right in uninoculated, sterilized soil.



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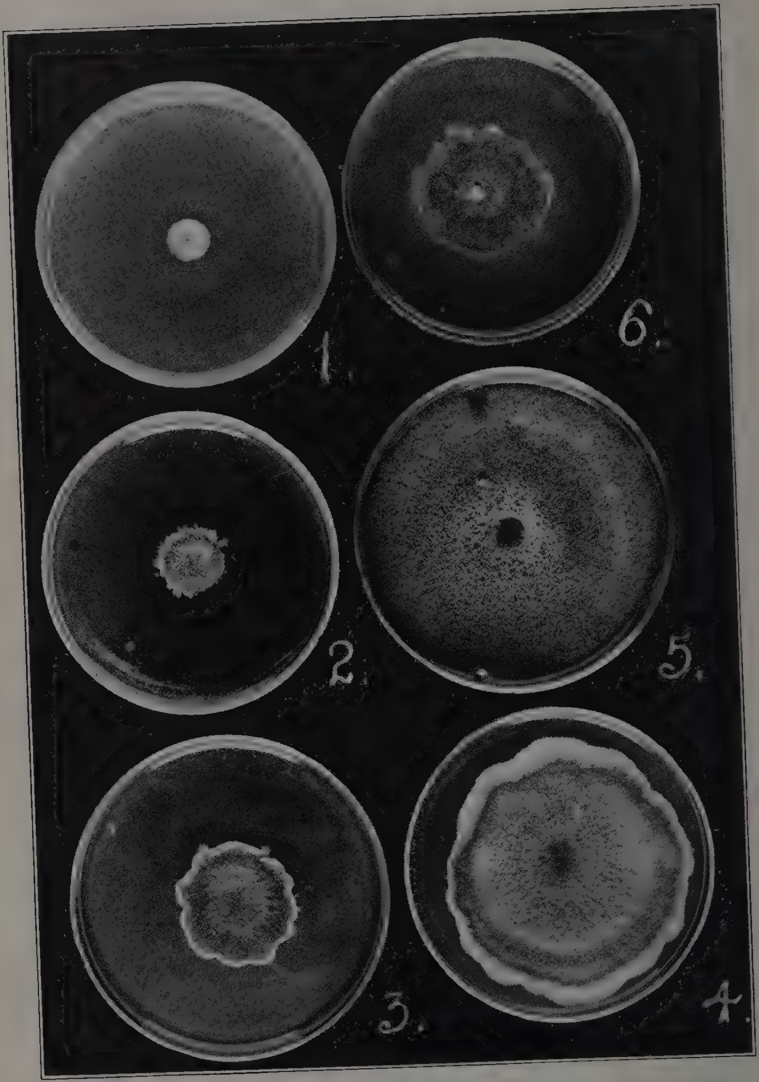


PLATE II

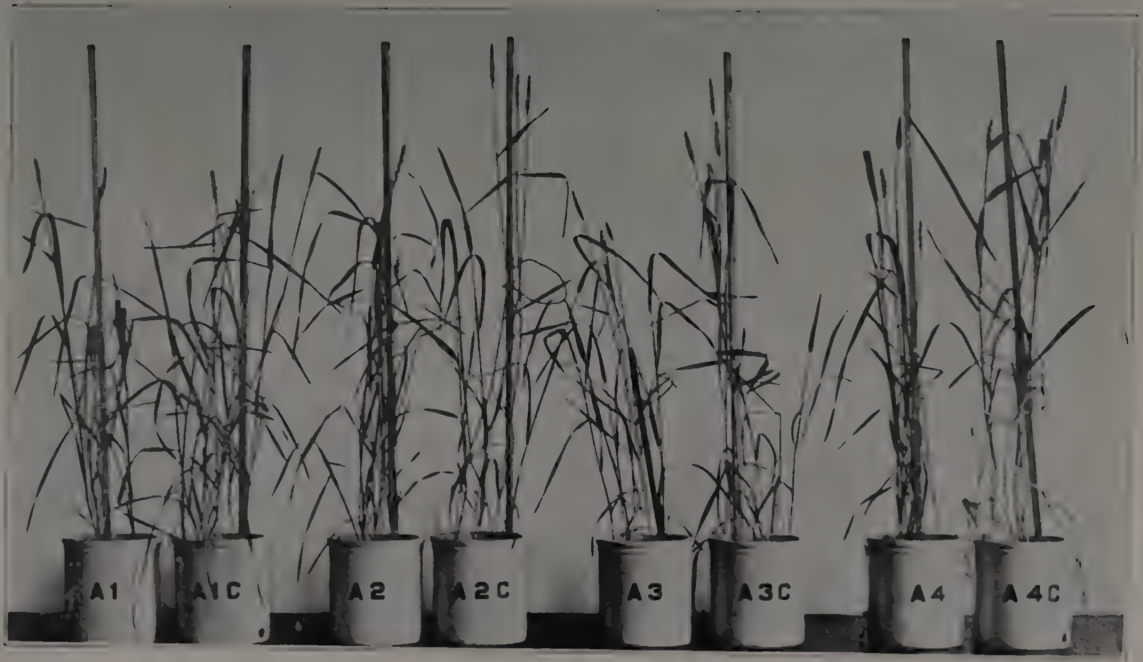


PLATE III

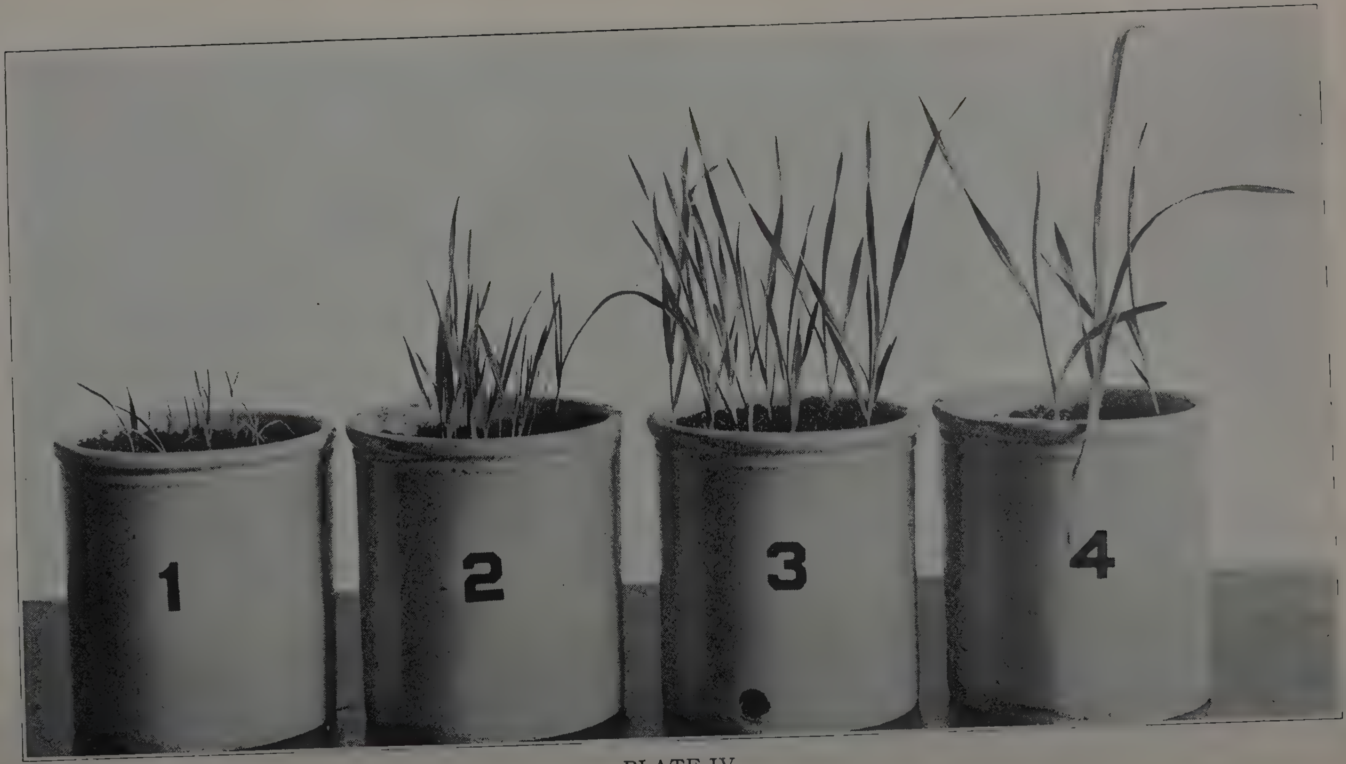
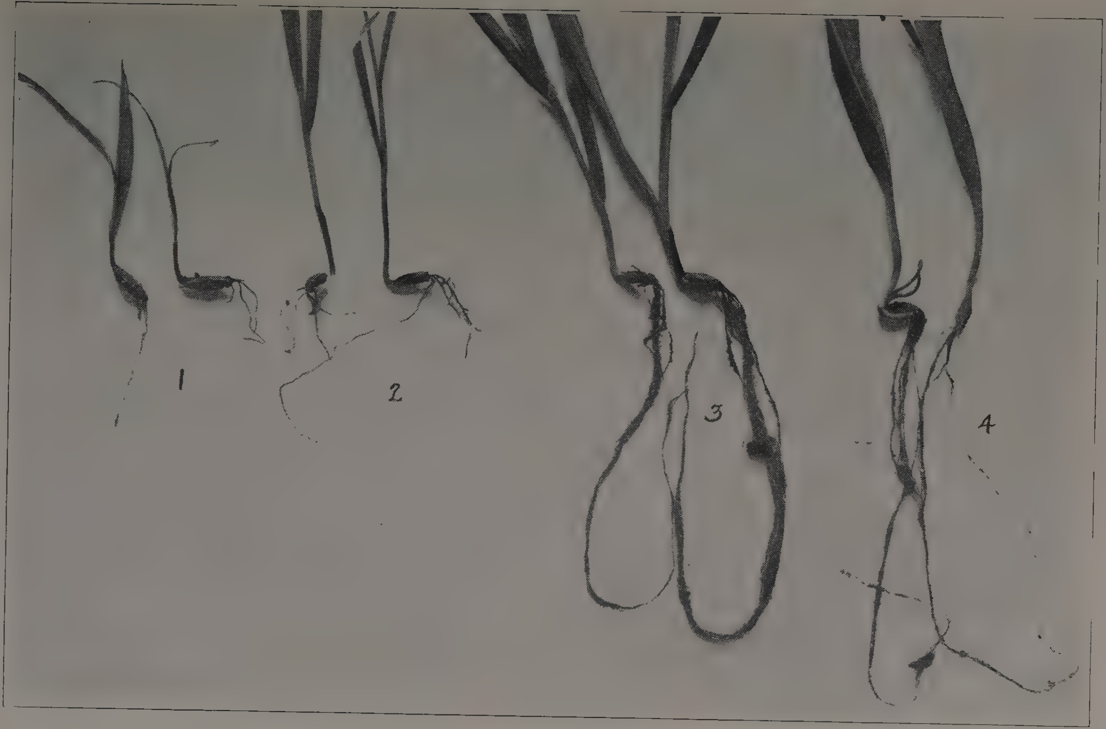


PLATE IV



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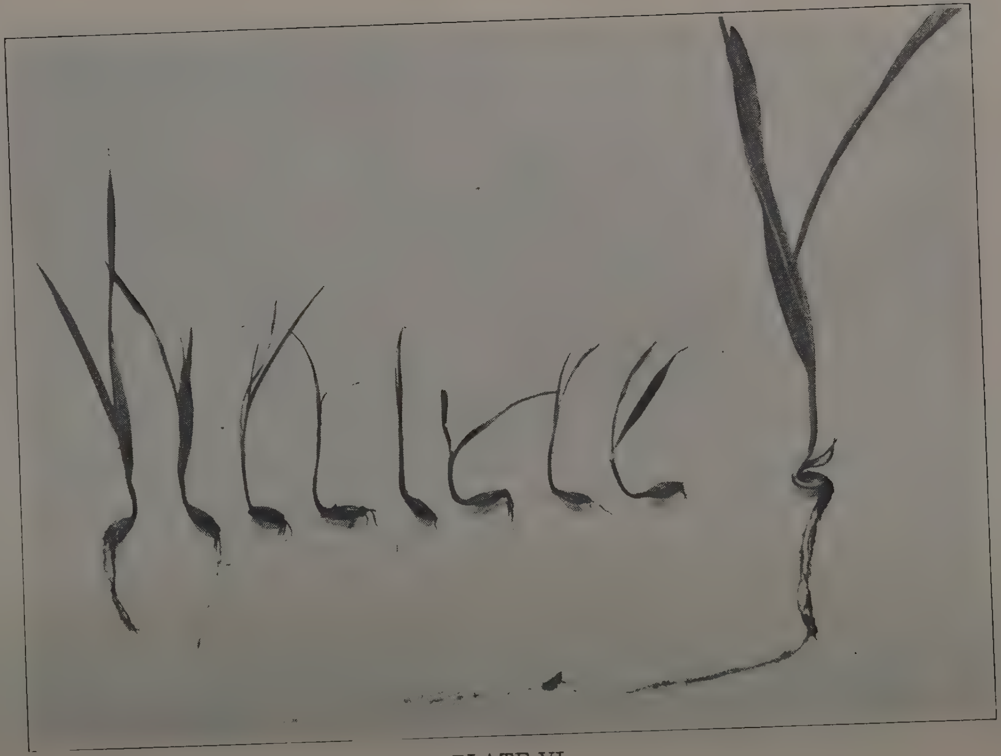

PLATE VI

Technical Bulletin 18 August 1923

The University of Minnesota
Agricultural Experiment Station

Wheat Scab in Minnesota

By Jean MacInnes and Raymond Fogelman
Division of Plant Pathology and Botany

UNIVERSITY FARM, ST. PAUL

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UNIVERSITY FARM, ST. PAUL

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WHEAT SCAB IN MINNESOTA

By Jean McInnes and Raymond Fogelman[1]

INTRODUCTION

Scab or "head blight" of wheat has been known in Minnesota for more than twenty years. The disease seems to have attracted little attention, however, until about 1915 when it became sufficiently prevalent, especially on Marquis wheat, to attract the attention of growers, who sent to the experiment station a great many diseased heads of wheat with the comment that head blight was doing a great deal of damage. Practically every one of these farmers said that Marquis was more severely injured than other varieties. Whether the introduction of Marquis and its general use was responsible for the increasing amount of scab is not definitely known, but it is certain that the disease seems to have become more prevalent with the general adoption of Marquis.

Altho considerable work already had been done on the disease, many facts concerning its general characteristics were still unknown when the writers began their investigations. The conditions most favorable for its development, the plants attacked, the distribution in the state, the amount of damage caused by the disease, and especially the control measures were known only very imperfectly. For this reason work on these various phases of the problem was begun in 1915 and has been continued until the present time. The major part of the work was completed in 1920 and little has been done since.

HISTORICAL SUMMARY

Smith (32) apparently first described wheat scab in England in 1884. He stated that the disease was caused by *Fusarium culmorum* and named it "wheat scab." In 1890 Kirchner (16) stated that a similar organism caused a disease of wheat, oats, barley, rye, and maize in Germany. Chester (5) seems to have been the first to call attention to the seriousness of wheat scab in the United States. In 1890 he mentioned the disease as having been serious in Delaware in that year. Arthur (2) mentioned the disease as being destructive in Indiana in 1891, and Miss Detmers (6) called attention to the disease in Ohio in the same year. Miss Detmers considered the cause of the disease to be *Fusarium culmorum* (W. G. Sm.). Pammel (18) also noticed the disease in Iowa that year, and Buckhout (4) said that the disease was abundant in Pennsylvania in 1892. Bessey (3) stated that the disease was prevalent in Nebraska a few years later. Since the disease already seemed to be widespread in the early nineties, it is quite likely that it had been in the country for some time.

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[1] The work in this paper was done under the direction of Dr. E. C. Stakman, head of the section of plant pathology. The writers wish to express their appreciation of his advice and criticism.

The early reports mention mainly the appearance of the disease on the heads of wheat, and Rostrup (23, 24, 25, 26) appears to have been the first to show definitely that the causal organism might live over in the seed and cause seedling infection. According to von Tubeuf (33), Rostrup also described a seedling blight of oats in Denmark in 1893 which was caused by an organism similar to that which causes wheat scab. Tubeuf also says that Frank found a field of rye near Kiel, in Germany, in which the heads were almost completly destroyed by scab. Selby (27, 28) called the conidial stage of the causal organism *Fusarium roseum* Link and the perfect stage *Gibberella saubinetii* (Mont.) Sacc. Selby and Manns (30) published the results of rather extensive investigations in 1909, and reported, as a result of cross-inoculation experiments, that the scab organism infected wheat, oats, barley, and rye. They considered that the different organisms previously described as causing scab probably were the same. They also demonstrated that the fungus persisted in the seed and might destroy young seedlings grown from the infected seeds. In addition they isolated pure cultures of the scab fungus from alfalfa plants that were dying in the field. Later, Selby (30) listed in his handbook on plant diseases the following hosts for the wheat scab pathogene: alfalfa, barley, clover, corn, emmer, oats, rye, speltz, and wheat. Appel and Wollenweber (1) found that *Fusarium culmorum* could rot potato tubers, and Lewis (17) identified a Fusarium which caused a rot of squash in storage as *F. culmorum*. E. C. Johnson (13) showed that a culture of *F. culmorum* which he isolated from wilted oats caused a decrease in the germination of wheat, oats, and barley seeds inoculated with it. Wollenweber (35), in 1914, stated that *F. culmorum* was a wound parasite of cereals and caused scab and seedling blight. He found that it could rot sweet potatoes and states that it also had been isolated from corn, oats, wheat, rye, barley, lupin, cotton, sweet potato, cucumber, squash, and other plants. Harter, Weimer, and Adams (8) also found that *F. culmorum* and *G. saubinetii* could rot sweet potatoes. Apparently, therefore, the organism was very prevalent in nature and was capable of attacking, at least to a limited extent, several host plants.

The wheat scab organism was considered to be particularly destructive only to wheat until comparatively recently, when it was shown that it is also a destructive parasite of corn. Pammel, King and Seal (19, 20) showed that *Fusarium sp.* causes corn root-rots and also attacks the stalk and the ears of the corn plant. Hoffer and Holbert (9, 10) also showed this to be true. Furthermore, they (10) observed that wheat following corn was likely to be more scabby than wheat following wheat. In the same year, Hoffer, Johnson and Atanasoff (11) reported that cultures of *G. saubinetii* isolated from corn roots and stalks produced typical wheat scab. They obtained similar results by inoculating both wheat and corn with cultures isolated from infected wheat plants. Holbert, Trost and Hoffer (12) observed that various systems of rotation affected the amount of scab in wheat very considerably. They found that wheat sown on land which had grown two successive crops of corn was more severely injured by scab than that grown on land which had grown wheat the previous year or than wheat which was grown on land following oats. Johnson, Dickson and Johann (15) found that *Gibberella saubinetii* apparently was the principal cause of the epidemic of scab of cereals in 1919, and Hoffer and Holbert (10) found that the same organism was responsible for a great deal of the root- and stalk-rot of corn.

GEOGRAPHIC DISTRIBUTION AND ECONOMIC IMPORTANCE

Scab has been reported on cereals in England, France, Germany, and Denmark, altho it seems that the disease is not so important in those countries as it is in the United States where it now ranks as one of the very destructive diseases of wheat and corn.

The general distribution of the disease in North America is shown in Figure 1. It has been reported from practically all wheat growing regions of the United States east of the Rocky Mountains as well as from Utah and Oregon. In Canada it seems to be most prevalent in the maritime provinces, Nova Scotia, Quebec, Ontario, New Brunswick, and Prince Edward Island. In 1919 it was quite destructive in those provinces and also appeared in southern Manitoba and in Saskatchewan.[2]

In Minnesota, scab of wheat has been most prevalent in the southern, southwestern, and west central wheat growing counties. It occurs in the Red River Valley, but is seldom as destructive as in the southern part of the state. Whether this is because more corn is grown in the southern half of the state, or because of the difference in climatic conditions, is uncertain. However, it seems to be quite clear that the disease on wheat is much more prevalent and serious in the corn-growing regions of the state. On the other hand, the rainfall in the southeastern section may be as high as 40 inches, while in the vicinity of Crookston, in the Red River Valley, it averages only about 18 inches. It is probable that both these factors influence the distribution.

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[2] Data furnished by Professor W. P. Fraser, Dominion Laboratory of Plant Pathology, University of Saskatchewan, Saskatoon, Saskatchewan.

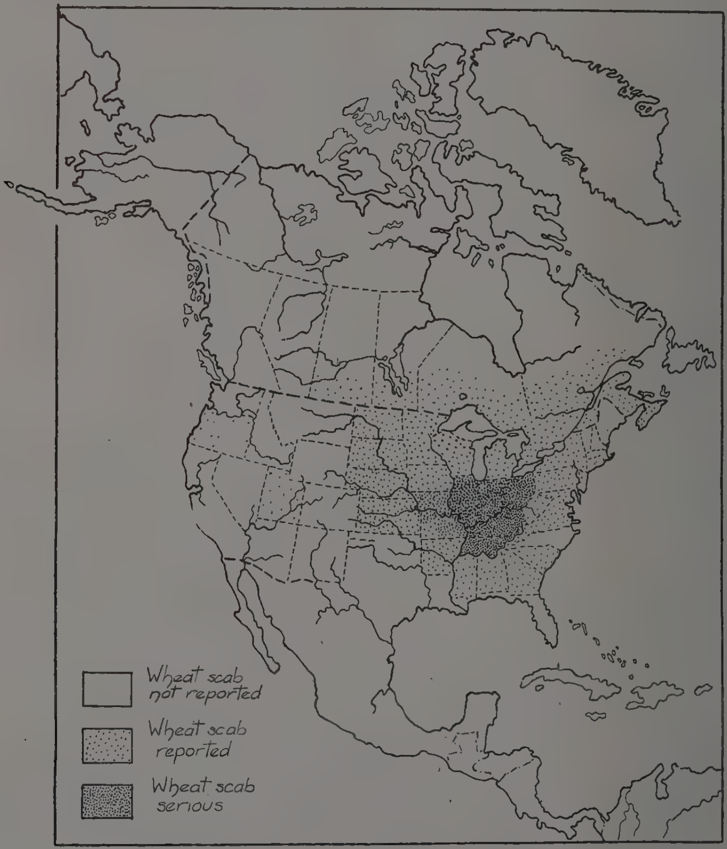

Fig. 1. Geographic Distribution of Wheat Scab in North America

The area where scab is reported serious corresponds closely with that of the production of soft red winter wheat in the United States.

The damage done by the wheat scab organism varies from year to year. In some years it becomes epidemic, while in others it does relatively little damage. For instance, there seem to have been severe attacks of scab in 1905 and 1907; and in 1915 it was destructive, the total loss on wheat being estimated at 5 per cent. In 1916 there was considerable, but not so much as in 1915. The disease did little damage in 1917 and 1918. In 1919 and 1920 the yield of both spring and winter wheat in Minnesota, especially in the southern half of the state, was greatly reduced by scab. A similar epidemic occurred throughout the wheat growing regions of the United States in 1919 (14, 21, 22), about five per cent of the total crop having been destroyed.

The root-, stalk-, and ear-rots of corn caused by the scab organism appear to be less prevalent in Minnesota than in some of the states farther south and east. This may be because the development of the disease is influenced by temperature (34). Thus only occasional isolated fields seem to be seriously damaged in Minnesota, while the disease is often very serious in the more southern parts of the corn belt. In both 1919 and 1920 the estimated decrease in yield due to this disease was about four per cent of the total corn crop of the country (21, 22).

SYMPTOMS OF SCAB ON WHEAT

Symptoms of scab on wheat are most conspicuous and characteristic on the heads. The disease may become evident soon after the heads have emerged from the sheath, altho it may not become apparent until much later. Affected spikelets often appear to have ripened prematurely, while healthy spikelets are still green. The glumes of the diseased spikelets, however, are usually pale and sickly, especially when they have been attacked while still young; and they may be partly covered with a varying amount of white or slightly pinkish mycelium. They are often cemented together by a smooth pinkish, orange, or reddish incrustation. The number of affected spikelets in a head various greatly; only a single one may be affected or nearly all may be diseased. In fact, when the organism attacks any part of the rachis the entire head above the point of attack may be killed. This occurs quite frequently in a bad scab year. The affected portion of the rachis at first appears water-soaked, and later becomes dark in color. Still later the dark color may disappear and the rachis appear somewhat bleached. The small dark perithecia usually develop later in the season (Plate I, Fig. B).

The appearance of the affected kernels depends largely upon the age at which the head is attacked. If still very young, practically nothing but the seed coats may remain and these are often covered with the whitish or pinkish mycelium. If kernels develop they are usually very small, much shrunken, and can easily be crushed between the fingers. When the kernels become infected after they have developed to a considerable extent they may be less shrunken, but usually have the same general appearance as the badly shrunken kernels (Plate I, Fig. A).

The upper part of the culms also may be attacked. The symptoms are quite similar to those on the rachis. The affected tissues first appear water-soaked and later become brownish or almost black in color. When the neck is attacked early, the heads often fail to develop normally and practically no viable kernels are produced.

On rye, barley, oats, and grasses the symptoms are similar to those on wheat.

The seedling blight caused by scab fungi can not easily be distinguished from that caused by several other fungi. The plants usually are stunted, the root system is small, the individual rootlets are often brown or pink and may decay rapidly. The base of the young shoots also may be attacked, in which case the entire seedling dies.

Seedling blight often appears in definite patches in the field, and the plants in areas of considerable size are sometimes killed. This may be because the organism has accumulated in the soil, altho this has not been definitely proved. This occurrence apparently is associated with definite weather conditions. Unfavorable environment may allow the organism to reduce the stand greatly. Some of the attacked plants, however, may recover and mature if weather conditions again become favorable to the crop. Such plants may be stunted, but apparently are no more subject to head blight than are other plants.

ETIOLOGY

The principal cause of wheat scab in Minnesota is probably *Gibberella saubinetii* (Mont.) Sacc. (*Fusarium graminearum*) Schwabe. This organism was found (15) to be primarily responsible for the epidemic which occurred throughout the middle western wheat growing regions in 1919. Other organisms, apparently quite distinct from this one, have been isolated from scabby wheat and their pathogenicity has been proved. Very little is known regarding the comparative virulence of these different species, nor is it known whether their life histories are comparable. It has been definitely proved, however, that at least one of the organisms causing root-, stalk-, and ear-rots of corn is the same organism as the one chiefly responsible for the epidemic of 1919. Furthermore, as will be shown later, this same organism is capable of attacking a very wide range of host plants. To what extent these other species are capable of doing the same thing is not known.

In the experimental work described in the following pages, except where otherwise specified, a strain of Fusarium isolated from scabby wheat and identified as *Gibberella saubinetii* was used exclusively.[3] In the field work, however, especially where controlled inoculations were not made, the identity of the organism or organisms could not easily be determined.

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[3] Identified by Dr. Sherbakoff.

LIFE HISTORY OF ORGANISM AND SOURCES OF INFECTION

The complete life history, as far as spore forms are concerned, has been definitely determined for *Gibberella saubinetii.* In other cases only the conidial stages have been observed. An examination of Plate II will make clear the different stages through which *G. saubinetii* passes. Figure 1 shows the way in which the conidia are developed and Figure 2 the mature conidia germinating. In Figure 3 a few strands of the mycelium are represented. The second, or ascus, stage is illustrated by Figures 4 to 8. The conidia, the mycelium, and the spores formed in the ascus are all equally capable of causing infection, altho it seems probable that the ascospores, protected as they are by the perithecium (Fig. 4), are better able to resist unfavorable conditions than are the conidia.

It is clear, therefore, that infection may be brought about in several ways. Infected seed contains a large amount of mycelium which is capable of attacking any susceptible plant, and which may form spores if conditions are favorable,. Soil that has been under cultivation has been shown to contain large numbers of conidia which may attack the roots directly or may be blown by the wind and attack the heads. Conidia also may occur on a great variety of debris and thus form possible sources of infection. Furthermore, the perithecia occurring on old corn or wheat stubble are filled with ascospores which may be disseminated by the wind, by insects, or by other carriers.

To what extent these various sources of infection are important is not definitely known. It is extremely important, however, to determine the extent to which the conidia and mycelium of the organism are capable of living over winter and becoming a source of infection the following spring.

Scabby heads, infected kernels, and cultures of the organism were, therefore, kept outdoors at St. Paul during the winter of 1918-19 and similar experiments were made in 1919-20. The results are given in Tables I and II. Some heads, kernels, and cultures were kept in the laboratory, both in the dark and in the light, while others were kept under similar conditions outdoors. The mycelium and the spores retained their viability when they were kept in the dark inside and also when they were in the dark outside, but similar sets that had been exposed to the light were killed. The results show rather clearly that low temperatures alone are not sufficient to destroy the organism, especially when the fungus is protected under rubbish or straw in the field, and it is quite probable that it lives over winter without difficulty. Undoubtedly, large quantities of spores and considerable mycelium are protected from the apparently injurious effect of light, and can, therefore, develop normally when conditions are again favorable for growth.

TABLE I

EFFECT OF EXPOSURE ON VITALITY OF THE MYCELIUM OF *Gibberella saubinetii* IN SEEDS OF WHEAT

Kind of Seed	Location of material							
	Ice box 10° C.		Thermostat 25° C.		Cold store-room		Outside on ground	
	A*	B	A	B	A	B	A	B
Healthy	—†		—		—		—	
Scabby	+	—	+	—	+	—	+	—
Scabby	+		+		+		+	
Scabby	+		+		+		+	
Inoculated		+	+	+	+	+	+	+
Inoculated	+	+	+		+	+	+	—
Inoculated	+		+		+		+	+

* A — Exposed from October 1917 to April 1918 (6 months).
B — Exposed from October 1917 to April 1919 (18 months).
† + Organism alive when tested.
— Organism dead when tested.

TABLE II

EFFECT OF LIGHT ON VIABILITY OF CONIDIA OF *Gibberella saubinetii* EXPOSED UNDER VARIOUS CONDITIONS FROM OCTOBER, 1917, TO APRIL, 1918

Conditions under which kept and percentage of germination

Light		Dark	
Laboratory	Field	Laboratory	Field
0.0	0	50.0	100
1.0	0	75.0	100
0.5	0	0.5	90
0.0	0	85.0	100
0.0	0	25.0	50
0.0	0	100.0	90
0.0	0	25.0	50
Average 0.2	0	51.0	83

EFFECT OF TEMPERATURE

Temperature and moisture are known to be important factors in relation to scab on wheat. The disease is usually most prevalent in moist hot seasons. Experiments conducted in the field and laboratory were designed particularly to find the extent to which temperature is a factor in its development. No controlled experiments were made to correlate moisture and temperature with the development of scab, altho observation suggested very definitely that the disease is favored by high humidity when temperature conditions are right.

INFLUENCE OF TEMPERATURE ON ORGANISM

The rate of growth of the wheat scab organism on artificial media was studied at different temperatures. It was found that the organism grew most rapidly at temperatures between 25 and 27 degrees C. (77 to 80 degrees F.). At 30 degrees C. (86 degrees F.) the rate of growth is greatly decreased and the character of the mycelium produced is different from that produced at lower temperatures. No growth was obtained at 35 degrees C. (95 degrees F.). Dickson (7) found that the organism was killed at 33 to 34 degrees C. (91 to 93 degrees F.). On the other hand, the organism grows very slowly at 5 degrees C. (41 degrees F.) and according to Dickson does not grow at all at 3 degrees C. (38 degrees F.). These results obtained by the writers are shown in Table III and in Figure 2. (See also Plate III, Fig. A.)

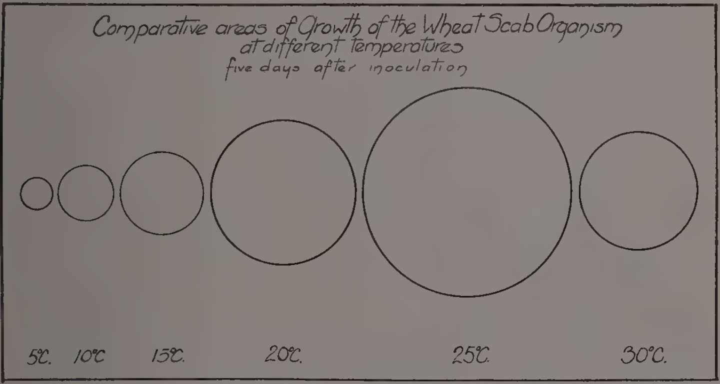

Fig. 2. Growth of Mycelium of *Gibberella saubinetii* in Relation to Temperature

TABLE III

Effect of Temperature on Growth of *Gibberella saubinetii* on Culture Media

Temperature in degrees C.	Time after inoculation in days					
	1	2	3	4	5	6
	Diameter of colonies in centimeters*					
5.0	†	†	†	†	†	†
10.0	†	0.6	1.6	1.9	2.5	2.5
15.0	1.0	1.5	2.5	2.7	3.0	3.5
20.0	1.0	2.5	3.7	5.7	6.8	8.0
25.0	1.2	3.0	5.6	8.2	9.9	..
27.5	1.3	4.0	3.9	6.6	8.5	10.0
30.0	0.8	2.4	4.1	5.9	6.0	6.5

* Figures based on averages of from 4 to 10 experiments.

† Trace.

Spore germination was found to occur most rapidly at temperatures near the optimum for growth of the mycelium (Table IV, and Fig. 3). At 25 degrees C. (77 degrees F.), practically 100 per cent of the spores germinated and the germ tubes were well developed aftr 48 hours; while at 10 degrees C. (50 degrees F.) only 40 per cent had germinated, the germ tubes being very short. Temperatures above 30 degrees C. (86 degrees F.) were found to decrease the percentage of germination as well as the length of the germ tube. However, practically all the spores eventually germinated at all the temperatures tried.

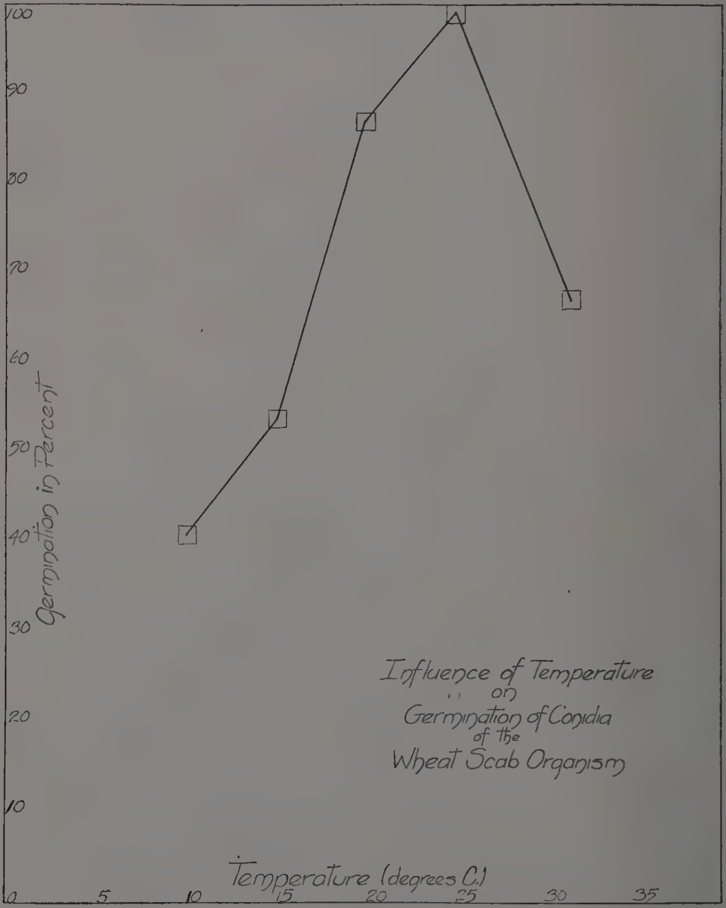

Fig. 3. Germination of Conidia of *Gibberella saubinetii* in Relation to Temperature Note that the optimum temperature is the same as for the growth of the mycelium.

TABLE IV

EFFECT OF TEMPERATURE ON GERMINATION OF CONIDIA OF *Gibberella saubinetii* IN DISTILLED WATER

Temperature in degrees C.	No. of spores counted	No. of spores germinated*	Percentage of germination
10	448	183	41
15	364	200	54
20	179	156	89
25	350	350	100
33	232	157	67

* Counts made at the end of 48 hours.

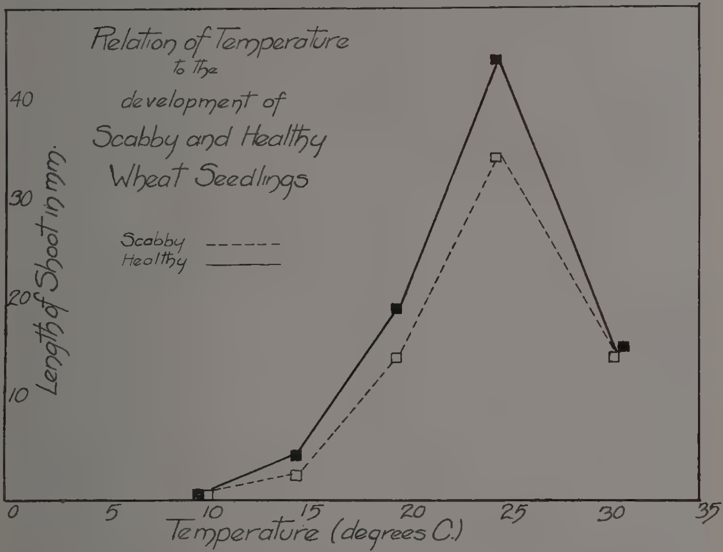

Fig. 4. Growth of Wheat Seedlings in Relation to Temperature

The shoots produced from scabby seeds were markedly stunted at temperatures favorable for the organism. At 30 degrees C., altho the plants grew slowly because of the high temperature, the seedlings from scabby seeds grew as rapidly as those from healthy seeds.

INFLUENCE OF TEMPERATURE ON GERMINATION OF WHEAT SEED

According to Dickson (15) wheat germinated normally at temperatures between 8 and 24 degrees C. (46 and 75 degrees F.), the rate of germination increasing up to 32 degrees C. (89 degrees F.). The results of the experiments carried out by the writers are more or less in accordance with those found by Dickson. The percentage of germination of the wheat kernel was not materially affected by temperatures between 5 and 33 degrees C. (41 and 91 degrees F.). The rate of development, however, was greatly changed (Table V) (Fig. 4). After four days in the germinator the shoots from seeds kept at 25 degrees C. (77 degrees F.) were from eight to ten times as long as those kept at 15 degrees C. (59 degrees F.). At 33 degrees C. (91 degrees F.) the rate was decreased considerably. At 5 and 10 degrees C. (41 and 50 degrees F.) they had not developed at all. However, if sufficient time was allowed, normal germination took place even at these low temperatures.

TABLE V

Effect of Temperature on Germination of Wheat Seed and on Development of Scab

Temperature in degrees C.	Kind of seed planted*	Percentage of germination†	Av. length of epicotyl in mm.	Percentage of blighted seedlings
5	Scabby	0	0	0.0
	Healthy	0	0	0.0
10	Scabby	0	0	0.0
	Healthy	0	0	0.0
15-16	Scabby	83	3	6.5
	Healthy	92	5	0.0
18-20	Scabby	79	15	7.3
	Healthy	98	20	0.0
25	Scabby	78	35	7.3
	Healthy	98	45	0.0
32-33	Scabby	79	15	2.0
	Healthy	96	15	0.0

* Seeds were planted in sterilized soil.

† At the end of four days.

INFLUENCE OF TEMPERATURE ON DEVELOPMENT OF SEEDLINGS FROM HEALTHY AND SCABBY KERNELS

Attention has been drawn to the fact that when scabby seed is germinated under normal conditions, considerable fungus growth develops, often in quantities sufficient to destroy the seedlings. It was found, however, that the amount of fungus growth thus produced varied considerably with the temperatures at which germination occurred. When scabby grain was germinated at temperatures between 30 and 33 degrees C. (86 and 91 degrees F.) relatively little fungus growth was produced and the young shoots in most cases escaped injury. Considerable mycelium was produced at temperatures from 20 to 30 degrees C. (68 to 86 degrees F.) usually in amounts sufficient to destroy the shoots and roots of the young seedlings in less than one week. From 10 to 15 degrees C. (50 to 59 degrees F.), however, the rate of fungus growth was considerably slower, and the seedlings usually developed too rapidly for the organism to attack them. It is seen, therefore, that temperature is an extremely important factor in determining the number of seedlings that will be killed, and that good growth may be obtained even when the organism is present, if the temperature is unfavorable to its growth. In order to demonstrate that the blighting of the seedlings was due directly to the presence of the organism and not to the shrunken condition of the seeds, a number of plump healthy seeds were sterilized and germinated.[4] Half of these were then inoculated with the wheat scab organism, and grown at different temperatures, the other half being retained as checks (Plate III, Fig. B.). The results (Table VI) were identical with those obtained when scabby seeds were used. Similar results were obtained also when scabby seeds were planted in pots and germinated at different temperatures (Table VII). It is obvious, therefore, that the blighting of the seedlings is due to the presence of the scab organisms and that the activities of these organisms are directly limited by temperature conditions.

No controlled experiments have been carried out to show the relation of temperature to the development of scab on the heads. However, observations in the field seem to indicate that more scab is produced at temperatures near the optimum for the growth of the organism than at other temperatures.

[4] The following method for obtaining sterile seedlings was used: Seeds were soaked in distilled water for thirty minutes. They were then immersed in 50 per cent alcohol containing 0.2 per cent mercuric bichloride. After washing in sterile distilled water, the seeds were put in petri dishes. The sterile germinating seeds were transferred to test tubes, containing agar, after four days' growth.

TABLE VI

Effect of Temperature on Blighting of Seedlings Grown in Sach's Nutrient Agar and Inoculated with *Gibberella saubinetii*

Temperature in degrees C.	Condition of seedlings and growth of organism			
	Third day		Seventh day	
	Average length of epicotyl in cm.	Average length of root system in cm.	Development of organism	Remarks
10	1.0	49	Nearly covering medium, growth slight.	Some aerial roots browned. *Check* clean.
15-16	3.5	120	Well developed.	Some roots in the medium. Three plants growing, three killed. *Check* growing out of tube.
18-20	2.4	*	Luxuriant.	Few roots developed, only one plant more or less escaping the organism. In all other cases both roots and plant killed. *Check* growing out of tube.
25	3.3	*	Very luxuriant growth.	Very few roots in the medium. All plants killed. Whole seedling browned. *Check* growing out of tube.
20-30†	3.1	*	About as 18-20 degrees C.	Very similar in development to plants kept at 18-20 degrees C. More root development. *Check* growing out of tube.
32-33	2.4	70	Slow, not covering medium.	All plants grown to top of tube. Roots in contact with organism killed, no others. Epicotyl normal. Many normal roots. *Check* growing out of tube.

* Difficult to estimate, owing to growth of organism.

† Twenty degrees C. at night, 30 degrees in the day.

TABLE VII

EFFECT OF TEMPERATURE ON GERMINATION OF HEALTHY AND SCABBY SEED IN STERILIZED SOIL

Temperature in degrees C.	Kind of seed	No. of seeds planted	No. of seeds germinated	Percentage of germination	Av. length of epicotyl in cm.
10-12	Scabby	40	0	0	0.0
	Healthy	40	0	0	0.0
15-16	Scabby	40	6	15	0.3
	Healthy	40	14	35	1.5
18-20	Scabby	40	18	45	9.5
	Healthy	40	17	42	8.2
25	Scabby	40	11	27	7.4
	Healthy	40	33	80	12.1
32-33	Scabby	40	12	30	3.5
	Healthy	40	15	37	5.7

HOST PLANTS

It is evident from the historical summary that the organisms causing wheat scab can attack a great many plants other than wheat. Typical scab on the heads has been found in Minnesota on various types of wheat, rye, barley, oats, spelt, emmer, einkorn, and several grasses. It has seldom, if ever, been abundant enough on oats to do any appreciable damage. On rye, however, it sometimes causes considerable injury and occasionally also on barley. It occurs commonly on several wild grasses. Local epidemics of the disease have been seen frequently on western wheat grass (*Agropyron smithii*) and it also occurs on quack grass (*Agropyron repens*), slender wheat grass (*Agropyron tenerum*), and some of the wild rye grasses (*Elymus spp.*). The organism also attacks corn, especially the roots, altho this disease apparently is not so prevalent in Minnesota as it is in the more southern portions of the corn belt. It was of particular interest to ascertain by means of artificial inoculations whether or not the organism could be made to attack plants other than those on which it is found in nature. A series of experiments was, therefore, carried out, in both field and laboratory, in which a large number of plants widely separated taxonomically were inoculated. In Table VIII are listed all the host plants on which the disease has been found in nature in Minnesota, and also those that have been infected as a result of artificial inoculations.

TABLE VIII

HOST PLANTS OF WHEAT SCAB ORGANISMS

Host plant	Artificial inoculation	Natural infection	Type of injury
Wheat—			
Triticum vulgare	+	+	Head blight and seedling blight
T. durum	+	+	Head blight and seedling blight
T. spelta	..	+	Head blight
T. dicoccum	+	+	Head blight
T. monococcum	..	+	Head blight
T. polonicum	..	+	Head blight
T. compactum	+	+	Head blight
T. turgidum	..	+	Head blight
Rye—*Secale cereale*	+	+	Head blight and seedling blight
Barley—*Hordeum vulgare*	+	+	Head blight
Oats—*Avena sativa*	+	+	Head blight
Grasses—			
Agropyron caninum	..	+	Head blight
A. smithii	+	+	Head blight
A. cristatum	+	..	Head blight
A. desertorum	+	..	Head blight
A. repens	+	..	Head blight
Alopecurus pratensis	+	..	Leaf spot
Phleum pratense	+	..	Leaf spot
Bromus inermis	+	..	Leaf spot
Hystrix patula	+	..	Leaf spot
Elymus canadensis	+	..	Head blight
E. robustus	+	..	Head blight
E. virginicus	+	..	Head blight
Corn—*Zea mays*	+	+	Root rot
Bean—*Phaseolus vulgaris*	+	..	Root, pod, leaf and stem rots
Apple—*Malus sylvestris*	+	..	Fruit rot
Carrot—*Daucus carota*	+	..	Rot of storage organ
Potato—*Solanum tuberosum*	+	..	Tuber rot
Pea—*Pisum sativum*	+	..	Stem rot and seedling blight
Clover—*Trifolium pratense*	+	..	Seedling blight
Tomato—*Lycopersicum esculentum*	+	..	Stem and leaf rots and seedling blight
Flax—*Linum usitatissimum*	+	..	Seedling blight
Cucumber—*Cucumis sativus*	+	..	Stem rot and seedling blight
Squash—*Cucurbita maxima*	+	..	Stem rot
Sunflower—*Helianthus annuus*	+	..	Stem rot
Radish—*Raphanus sativus*	+	..	Seedling blight

PARASITIC CAPABILITIES OF THE ORGANISM

The effect produced on the different hosts and different parts of the same host by artificial inoculation varied considerably. The methods of experimentation and types of injury obtained on the various hosts are given below.

INFECTION OF FRUITS AND TUBERS

The fact that *Fusarium culmorum* is capable of causing a rot of the potato tuber has been demonstrated by several investigators (7, 31, 36). In order to determine whether the scab organism used in this study could produce such a rot, and to compare the rate of rotting with that produced by Fusaria generally found causing tuber rots, several sound potato tubers were inoculated with *Gibberella saubinetii* and with *F. oxysporum* and *F. tricothecioides*. One tuber was also retained as a check. These tubers were then placed under a bell jar and kept at a temperature ranging from 25 to 28 degrees C.

It was found that all three organisms were exceedingly active in rotting potato tubers. *Gibberella saubinetii* produced a very extensive rot within six weeks after inoculation (Plate V, Fig. E) which was second only to the one produced by *F. tricothecioides*. The scab organism was also found to produce rots on carrots and apples. These rots were less extensive than that produced in the potato tubers, but nevertheless they were definite in character and indicative of the rot-inducing nature of the organism. Lewis (17) reports finding the scab organism causing a serious rot of squash in storage.

The fact that an organism is capable of causing a rot of storage organs, such as potato tubers, is not sufficient proof in itself that the organism under consideration is a virulent parasite. Successful infection of the living parts of a plant is necessary in determining the true parasitic nature of the attacking organism.

INFECTION THROUGH WOUNDS

The stems and leaves of several hosts were punctured and bits of mycelium of the wheat scab organism introduced into the wounds. The plants were than incubated in a moist chamber. The mycelium made considerable growth and spread into the tissues while in the incubation chamber. The plants fell over at the point of inoculation owing to the weakening of the tissues following the spread of the mycelium through them. Eventual death of the plant resulted in nearly all cases. Inoculation experiments similar to those described above were also carried out with *F. lini*, the flax wilt organism, and *F. martii*, known to cause root rot of beans, to determine whether any other Fusarium known to cause injury to a specific crop, was capable of attacking a wide range of hosts, as are the scab organisms. Both *F. martii* and *F. lini* seem to be specialized and limited in their parasitic capabilities, as far as tested, to attacking the roots of beans in the former and to the roots and leaves of the flax seedling in the latter. All the crops tested, other than those mentioned, seemed incapable of being parasitized by these organisms.

Plate V, Figures A1 and A2 show the effect of stem inoculation upon the bean plant, two weeks after inoculation. The shriveling of the stem is shown to have extended in both directions from the point of inoculation, the parts above being shriveled and dead. Attention is especially called to the healthy check plant (Fig. A). The punctures show very distinctly and indicate clearly that the death of the infected plants was not the result of the injury to the stem. Figures C and D show similar effects of the organism upon tomato and cucumber plants three days after inoculation.

Plate VI, Figure A, shows the wheat scab organism parasitizing the living parts of pea plants. The two plants in the pots to the left were yellow and dead, the one in the pot to the right remained healthy and green. Fig. B, of the same plate, shows the effect of scab cultures upon sunflower seedlings the stems of which had been inoculated ten days previously. The plants in the first and seventh pots, counting from the left, are check plants. The one in the third was inoculated with *F. lini.* It will be noted that these checks and the one inoculated with *F. lini* were the only ones that remained alive and vigorous.

Figure C shows the effect of the scab organism on squash plants. The check plant is in the pot to the right. The stem of the plant in the center pot is dead as a consequence of the successful infection. These two are shriveled and dead as a result of the infection, while those inoculated with *F. lini* are as healthy and vigorous as those of the check plant. This points once more to the difference in the virulence of the two organisms; to the specific limitations of the one and the wide adaptability of the other.

INFECTION OF UNINJURED TISSUES

The facts brought out in the above experiments show clearly the ability of the scab organisms to attack diverse crops and their extreme virulence as wound parasites. Scab of wheat is known to appear on uninjured heads of wheat. This would indicate that the wheat scab organism did not depend upon previous wounding of the tissues. However, tests were made on several hosts to test this point conclusively.

Artificial inoculations on individual heads of different varieties of wheat and several wild grasses were made in the field. Inoculations were made by inserting a small amount of the fungus (*Gibberella saubinetii*) inside the sheath, only those heads being chosen which had not completely emerged. Care was taken not to injure either the sheath or the head. Moist cotton was then wrapped around the sheath, the whole being covered with a wax-paper bag. These covers were left on for periods varying from three to seven days. By this method successful infections were obtained on several varieties of common wheat

(*T. vulgare*) as well as on durum (*T. durum*), emmer (*T. dicoccum*), and club (*T. compactum*) wheats. Rye, barley, oats, and several wild grasses were similarly infected (Table VIII).

It seems quite probable that the list of susceptible grasses given in Table VIII could be greatly enlarged if inoculations were made at the proper time. Many of the negative results obtained were without doubt due to the fact that the heads were too old at the time of inoculation. In every case, however, in which the inoculation gave positive results the heads were attacked in a manner exactly similar to natural infection. The effects shown in Plate IV are characteristic of the results obtained. A pink incrustation developed on the glumes, and the kernels either did not form or were small, shriveled, and covered with a mass of pinkish white mycelium. Typical scab also developed on all the varieties of wheat and other cereals inoculated, altho some of the varieties of wheat were more heavily infected than others. So many factors might be involved in this variation that no definite conclusions can be drawn.

Leaf spots were obtained in several cases and pure cultures of the organism were isolated from them.

The uninjured leaves of tomato and bean plants growing in the greenhouse were inoculated by placing growing mycelium on the surface. The upper surface of some leaves was inoculated and the lower surface of others. Upon removal from the incubating chamber, the fungus was found to have produced definite spots. The growth of the organism extended through the leaf, and pure cultures of the organism were readily obtained.

A vigorously growing bean pod was similarly inoculated without injury to the tissues. The mycelium spread throughout the pod, shriveling it. Pure cultures were obtained from the uninoculated side of the pod, indicating the extent of the spread of the mycelium through the tissues.

While these observations are preliminary in their nature, they are indicative of the fact that under certain conditions the scab organism may and actually does attack uninjured tissues.

INFECTION BY SOIL INOCULATION

A. DAMPING-OFF AND SEEDLING BLIGHT

Previous experiments show beyond doubt that the scab organism is a virulent parasite, and that it attacks a large number of unrelated hosts. Attention has been called by many investigators to the fact that *Fusarium spp.* are to be found connected with the damping-off of the seedlings of a large number of crops. The fact that the wheat scab organism is capable of attacking the seedlings of small grains has already been brought out. Efforts were made to determine whether the scab organism was capable of inducing such damping-off of hosts other than wheat.

The question of sick soils and the part played by the wheat scab organism in their production has already been discussed. This condition can be approximated closely by heavy inoculation of soil in pots. The soil was sterilized under steam pressure previous to inoculation in order to kill any organisms which might already be in the soil.

White clover was planted in such sterilized soil, the soil of one pot being inoculated with the scab organism, while that of the other was retained as a check. Two weeks after inoculation it was quite evident that the scab organism was killing many of the clover seedlings. The stems and roots of a large number of these were discolored and were beginning to rot. These dead parts were infected with the wheat scab pathogene. Plate V, Fig. B1 and B2, shows two such pots two weeks after inoculation. The effects were even more striking than the plates would indicate, altho the difference between the checks and the inoculated plants is very striking. Nearly half the plants in the inoculated pot were killed and the rest were stunted.

Pea, tomato, radish, cucumber, and flax seedlings were also grown under similar conditions. The flax wilt organism (*Fusarium lini*) was inoculated into the soil of one pot of each of these hosts in order to compare the parasitic capabilities of this organism with those of the scab organism. Typical wilt was produced on flax, some of the cotyledons becoming infected as they pushed their way through the sick soil, but no such wilt occurred on any of the other hosts. The scab organism, however, was capable of attacking and causing a seedling blight of all of these plants.

B. ROOT-ROTS

A disease known as dry root-rot of bean is caused by *Fusarium martii phaseoli.* To determine whether the wheat scab organism was also capable of attacking the roots of this host, several pots of soil were sterilized and beans grown in them. The soil of one of these pots was then inoculated with the wheat scab organism, that of a second with *F. martii,* and the third was retained as a check.

No important differences between the plants in the three pots were discernible until about six weeks after inoculation. By that time, however, many of the leaves of the inoculated plants had turned yellow and dropped off. These appeared less vigorous than did the plants in the check pot.

All the plants were then dug up (Plate VII, Fig. A). The stems and roots of the plants inoculated with *F. martii* showed large dark brown lesions, many of the roots having been killed and the whole root system reduced. This disease resembled very closely the condition described as dry root-rot. The plants from the pot inoculated with the scab culture (marked 200c in Plate VII, Fig. A) showed the same discolorations and reduction of the root system, only to a slightly less extent. The stems from both inoculated pots were beginning to shrivel and turn yellow, while those in the check pot, it will be noted, were entirely normal; and the root system, which was much better developed, showed no discolorations.

Several investigators have called attention to the fact that wheat scab is intimately connected with corn root-rot. Experiments were therefore made to determine whether the wheat scab organism used in these studies could produce this root-rot. Corn was planted in pots of sterile soil. The soil in some of these pots was then made sick with the wheat scab organism used in the inoculations on the roots of beans. The remaining pots were retained as checks. All the plants were then grown to maturity.

The plants in the inoculated pots were stunted in appearance during the whole period under observation, as compared with the check plants. (Plate VIII.) There was an average difference of 15 cm. in height between the two series of plants, the inoculated plants producing tassels two weeks later than the ones growing in the healthy soil. When the roots of the inoculated plants were examined they were found to be dark brown, shriveled, and beginning to rot, while those of the check plants were normal in every respect.

In order to study this root-rot more carefully, several pots of corn seedlings were inoculated with a wheat scab culture and an equal number were retained as checks. All the roots were examined a month later. The primary roots of the plants grown in the inoculated soil were dark brown, shriveled, and dead. Many secondary roots were similarly affected. Isolations made from these lesions yielded pure cultures of the scab organism. The roots of the check plants, however, were more numerous, better developed, and perfectly healthy. (Plate VII, Fig. B.)

CONTROL

No entirely satisfactory methods of control of wheat scab are known. The problem is greatly complicated by the number of hosts which the organisms causing the disease are capable of attacking and also because these organisms can grow saprophytically on almost any kind of debris.

Various measures have been suggested by workers in this country, such as burning of stubble, cleaning of seed, rotation of crops, etc., but none of these has controlled the disease, altho without doubt, under certain conditions, they would help to prevent its spread. Experiments were carried out in the field and in the greenhouse to test the efficiency of these methods. The results are rather contradictory in some cases and many of the experiments would have to be extended over several years before definite conclusions could be drawn. However, they are suggestive and may be of value in interpreting future work.

CLEANING AND TREATING SEED

In 1917 and 1918 the shriveled kernels from scabby seed were separated from the plump kernels by fanning, and part of each grade was treated with formaldehyde. One square rod each of the treated and untreated lots was planted. The results given in Table IX indicate that treatment of seed has no effect on the appearance of scab on the mature heads, the plots of treated seed in these experiments having a slightly higher percentage of scab than those of untreated seed. However, an examination of Table X, a record of plants grown under controlled conditions in the greenhouse, will show that treatment with formaldehyde materially increases the percentage of germination of scabby seed altho no scab appeared on any of the mature plants. The results shown in Plate IX are typical of those obtained in this experiment.

Planting scabby, untreated seed lowers the average germination of the seed and healthy seedlings may be attacked by the organism and be killed in the soil. Treatment, therefore, may be of some value in preventing seedling blight. The plants that survive the seedling stage, however, apparently may grow to maturity and produce healthy seed unless subsequently infected. In other words, infection is local and not systemic.

ROTATION OF CROPS

Many organisms causing plant diseases are known to accumulate in the soil when crops on which they are capable of developing are grown on the same land for a succession of years. This is particularly true of organisms causing root-rots and of those that are able to live saprophytically during a part of their life. The organisms causing wheat scab are known to be abundant in soil in which wheat has been grown for a long time.

TABLE IX

Effect of Planting Treated and Untreated Seed in the Field on the Percentage of Scabby Heads

Kind of seed	Treatment			
	Formaldehyde (1:320)		None	
	Percentage of scabby heads			
	1917	1918	1917	1918
Healthy	1.66	0.79	0.35	0.79
Scabby	1.12	1.14	0.80	0.21

TABLE X

Effect of Treatment with Formaldehyde on Percentage of Germination of Wheat Seeds and on Percentage of Scab at Maturity*

Kind of seed	Treatment	No. of pots	No. of seeds per pot	Percentage of germination	Percentage of scab at maturity
Healthy	None	25	10	89.6	0
Scabby	Formaldehyde†	25	10	81.6	0
Scabby	None	25	10	21.2	0

* Unpublished data from observations made in the greenhouse in the winter of 1917 by W. N. Christopher.

† Strength 1:320.

In 1918, in Indiana, Hoffer, Johnson and Atanasoff (11) observed that the percentage of scab on wheat that was planted on land where root-rot of corn had been prevalent the year before was much higher than on wheat following other crops. Inoculation experiments proved that the organism causing corn root-rot was identical with one of the organisms which cause wheat scab and was capable of producing scab on wheat. These results were very suggestive as to a method of spread of the disease. In 1919 a careful summary of the plant disease survey of Minnesota made by the United States Department of Agriculture showed a much higher average percentage of scab on wheat grown on corn land than on wheat grown after either wheat, rye, or barley (Table XI). Results for several years must be obtained before definite conclusions can be drawn, but it is possible that the organism can very readily live over winter on diseased corn stubble and be in a condition to attack the susceptible wheat plant as it matures.

TABLE XI

Effect of Rotation on Percentage of Scab on Wheat in Minnesota in 1919*

Previous crops	No. of fields visited	Average percentage of diseased heads	Yield in bushels per acre
Corn	193	23.53	5.62
Wheat	95	7.42	11.23
Oats	67	10.81	10.03
Barley	20	11.15	10.75

* Data taken from the Plant Disease Survey of the United States Department of Agriculture for the year 1919.

VARIETAL RESISTANCE OF WHEAT

Many plant diseases have been very effectively controlled by the use of varieties which were more or less resistant to these diseases. Wheat scab is much more prevalent on some varieties of wheat than on others. Observations throughout the state as well as controlled experiments in the field and greenhouse have been made for several years. Prior to 1914, scab seemed to be really destructive in Minnesota only to durum wheats, but as soon as Marquis was introduced, farmers complained that this variety was more severely injured than any of the other common spring wheats. In 1919 there was a destructive epidemic of scab in the southern half of Minnesota. In Meeker and Kandiyohi counties, counts were made of the percentage of scabby heads in several neighboring fields of Marquis, Haynes bluestem, and Preston. The percentage of scabby heads, as well as of blighted spikelets, was consistently higher in Marquis than in the other two varieties. The percentage of scabby heads in Marquis ranged from 50 to 90, while that in the other varieties seldom exceeded 25. This might be because conditions for infection were more favorable when Marquis was in flower, but, whatever the cause, Marquis was more severely injured than the other two varieties.[5] These results are similar to the averages obtained by the Plant Disease Survey for the whole state in 1919 (Table XII).

TABLE XII

VARIETAL SUSCEPTIBILITY OF WHEAT TO SCAB IN MINNESOTA IN 1919*

Variety	No. of fields visited	Average percentage of scab
Marquis	325	16.80
Preston	83	12.74
Durum	19	4.97
Haynes bluestem	12	1.40

* Data from Plant Disease Survey of 1919.

In order to determine more accurately the comparative susceptibility of wheat varieties to scab, attempts were made at University Farm to develop artificial epidemics. Different varieties of wheat were grown on corn land and the emerging heads were sprayed with a suspension of spores of various scab-producing organisms. Unfortunately, it was not possible to obtain as high a percentage of scab as would be desirable for accurate conclusions. The data are therefore preliminary, but some indications of comparative susceptibility were obtained. Tests were made in 1917, 1918, 1919, 1920, and 1921, but only in 1918 and 1921 did enough scab develop to warrant any conclusions. The results are summarized in Tables XIII and XIV.

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[5] Observations made by E. C. Stakman, H. K. Hayes, and R. J. Garber.

TABLE XIII

RELATIVE PERCENTAGE OF SCAB ON VARIETIES OF WHEAT ARTIFICIALLY INOCULATED IN THE FIELD IN 1918

Variety	No. of heads counted	No. of scabby heads	Percentage of scabby heads
Mindum, Minn. 470	740	117	16.2
Glyndon Fife, Minn. 163	923	27	3.0
Preston, Minn. 188	873	22	2.6
Marquis, Minn. 1239	1067	24	2.2
Velvet Don, Minn. 1364	814	18	2.1
Stanley, Minn, 1594	883	8	0.9

TABLE XIV

COMPARATIVE RESISTANCE OF WHEAT VARIETIES TO SCAB AT UNIVERSITY FARM IN 1921*

Variety	Percentage of scabby heads		Percentage of scabby seeds from infected heads	
	A†	B†	A	B
Preston, Minn. 924	0.0	0.5	0.0	3.0
Haynes Bluestem, Minn. 169	1.0	0.5	9.0	4.0
Glyndon Fife, Minn. 163	1.5	0.0	11.0	0.0
Kota, C. I. 5878	1.5	3.0	8.0	9.8
Kitchener, C. I. 2153	2.5	1.5	10.3	10.5
Ruby, C. I. 2151	2.5	3.0	28.0	18.0
Prelude, C. I. 4323	2.9	3.6	8.1	15.0
Red Bobs, C. I. 6255	2.5	8.3	11.0	23.0
Red Durum, selection	3.0	11.0	12.0	12.1
Marquis, Minn. 1239	4.5	9.5	19.0	18.0
Acme, C. I. 1967	6.5	8.5	19.0	12.3
Kubanka, C. I. 2102	8.8	7.9	27.7	10.0
Monad, C. I. 2156	12.0	10.0	18.0	14.5
Mindum, Minn. 470	14.5	9.0	14.1	16.6
Kubanka, C. I. 2094	19.5	14.0	13.0	18.8
Kubanka, (8) C. I. 4063	...	25.4	...	11.4

* Data furnished by J. J. Christensen.

†A. Planted April 23, 1921.
B. Planted May 10, 1921.

DISCUSSION OF CONTROL MEASURES

It is evident that control of wheat scab is difficult for the following reasons: The organism may grow on a great many cultivated and wild hosts; it may live as a saprophyte on dead materials; it may live a long time even under comparatively unfavorable conditions; and it is easily distributed by the wind and other carriers. The only methods of control that can be recommended at present are thoro fanning and treatment of seed grain, proper crop rotation, and the use of resistant varieties.

While scab can not be controlled entirely by the use of clean seed, the amount of seedling blight can be reduced considerably if only healthy plump seed is sown. Seed grain should be fanned very thoroly in order to blow out all the light, shriveled kernels. The treatment used for the control of stinking smut will kill any spores on the surface of the seed. Very badly scabbed seed lots should not be planted. Wherever possible seed should be obtained from fields in which there had been very little scab.

Rotation of crops is important in controlling the disease. It has been found that scab in wheat is likely to be much more severe when this crop follows corn. In fact, scab is likely to be more prevalent in wheat that is grown on corn land than in wheat which follows wheat or other cereal crops. While it would be unwise to recommend that wheat should never follow corn, it seems perfectly clear that in those regions in which scab is destructive nearly every year the amount of damage could be reduced considerably if some system of rotation were devised which would avoid sowing wheat on corn land.

Early sowing may aid somewhat in keeping down the amount of seedling blight. The fungus which causes scab is likely to develop most profusely at fairly high soil temperatures. Early sowing, therefore, is likely to enable the wheat to grow away from the scab.

Sanitation is quite important. It should be remembered that the scab organism attacks a great many wild grasses as well as the small grains and corn. For this reason it would be well to keep down the wild grasses as much as possible. Grasses along fence rows and roadsides near the grain fields may be the source of a great deal of infection in the spring. Clean cultivation in the fullest sense is likely, therefore, to reduce the amount of scab somewhat. This would be particularly effective if all farmers in a community followed the same practice.

Epidemics of scab are likely to occur when weather conditions are favorable for its development, in spite of the precautions enumerated. As the organism which causes the disease is carried by the wind, co-operative effort over a large area would be necessary in order to reduce the amount by the methods described. The only hope of controlling the disease seems to be in the development of resistant varieties.

Unfortunately, Marquis, the most popular hard red spring wheat, is extremely susceptible to scab. Preston, Haynes bluestem, and some of the other hard red spring wheats which are not now grown extensively, are much more resistant than is Marquis. It is hoped that it will be possible eventually to obtain scab resistant wheats which have other desirable characters as well.

SUMMARY

1. Scab of wheat has been known in Minnesota for more than twenty years. The disease appears to have become more prevalent with the general adoption of Marquis wheat, a variety which is very susceptible to scab.

2. The disease was first described in 1884 in England by Smith, who named it "wheat scab." Since that time it has been the subject of numerous investigations but there is yet much to be learned about the disease.

3. The disease is widespread in Europe, Australia, and North America. It is apparently more severe in North America than in Europe or Australia. It is most destructive in the corn belt of the United States, where it often does great damage.

4. Scab causes a head blight and a seedling blight of wheat. On the heads the disease becomes evident soon after the blooming period. Affected spikelets appear to have ripened prematurely, and under certain conditions, are covered with white or pinkish fungous mycelium. They are often cemented together with a pink or orange incrustation. Affected kernels are shriveled and discolored. The seedling blight in general can not be distinguished from that caused by other fungi. The young plants may be either stunted or killed.

5. The principal cause of wheat scab in Minnesota is probably *Gibberella saubinetii* (Mont.) Sacc. (*Fusarium graminearum*) Schwabe.

6. Infection may be brought about in several ways: namely, through infected seed, infested soil, debris, and corn stubble. Spores from these sources may be disseminated by wind, insects, or other carriers.

7. Over-wintering experiments demonstrated that mycelium and spores may live over winter in Minnesota if protected from the injurious effects of light.

8. The cardinal temperatures for the pathogene on artificial media are: 3 degrees, 25 to 27 degrees, and 33 degrees, C.

9. Spore germination is most rapid at temperatures near the optimum for the growth of the mycelium.

10. Normal wheat seed germinated between 5 and 33 degrees C., the best germination occurring at approximately 25 degrees.

11. When scabby seed were germinated at temperatures between 30 and 33 degrees C., the scab fungus grew so poorly that the seedlings in most cases escaped injury. The same was true when they were germinated at from 10 to 15 degrees C.

12. Field observations indicate that the disease develops most rapidly at temperatures near the optimum for the growth of the pathogene.

13. Various types of wheat, barley, and rye are susceptible. Oats are only slightly susceptible, but many grasses may be heavily infected.

14. By artificial inoculation and observations of natural infections the host range of the pathogene has been extended to many hosts widely separated taxonomically. The organism caused seedling blight of flax, clover, tomato, radish, pea, and cucumber; a stem rot of squash, bean, tomato, cucumber, pea, and sunflower; and rot of apples, carrots, and potato tubers. Living, uninjured leaves of tomato plants and both leaves and pods of bean plants were infected artificially, and the organism was reisolated from the attacked tissues. A root rot of bean, similar to the one found naturally on corn, also was obtained.

15. No entirely satisfactory control measures for wheat scab are known. Experiments showed that planting scabby untreated seed lowers the percentage of germination and introduces virulent cultures of the organism into soil in close proximity to the healthy seedlings, making them more liable to attack. Fanning, treatment of seed, and other sanitary measures, therefore, may be of some value in preventing seedling blight.

Crop rotation also seems to reduce the amount of disease. A survey of Minnesota in 1919 showed a much higher average percentage of scab on wheat grown after corn than on wheat after wheat, rye, or barley.

16. Observations and experiments have demonstrated wide differences in susceptibility of different varieties of wheat to scab. A resistant variety possessing other desirable agronomic characters, however, is not yet known.

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LEGENDS FOR PLATES

Plate I. Scab on Kernels and Heads of Wheat Naturally Infected

Fig. A1 and A2. Equal numbers of scabby and healthy kernels.

Fig. B. Infected head of wheat showing small black perithecia as they appear late in the season.

Plate II. Wheat Scab Organism, *Gibberella saubinetii* (Mont.) Sacc. (*Fusarium graminearum* Schwabe)

Fig. 1. Conidiophores from which vegetative spores are formed.

Fig. 2. Vegetative spores in process of germination.

Fig. 3. Strands of vegetative mycelium.

Fig. 4. Mature perithecium of the ascus or sexual stage of the organism.

Fig. 5. Detail of perithecial wall.

Fig. 6. Group of asci from within the perithecium showing immature asci.

Fig. 7. Mature ascus with ascospores.

Fig. 8. Mature ascospores.

Plate III. Relation of Temperature to Growth of Wheat Scab Organism

Fig. A. Relation of temperature to growth of mycelium (five days after inoculation).

1. 5°C. (41°F.) 2. 10°C. (50°F.) 3. 15°C. (59°F.)
4. 20°C. (68°F.) 5. 25°C. (77°F.) 6. 30°C. (86°F.)

Note that above the optimum (25°C.) the character of growth is different from that at the optimum and below.

Fig. B. Relation of temperature to seedling blight of wheat

Seedlings of wheat are inoculated with wheat scab organism and kept at different temperatures. Seven days after inoculation. Tubes at the right at each temperature are checks. Note that the shoots as well as the roots are killed at temperatures favorable for the development of the organism (19-25°C.). At temperatures above and below, the roots and shoots developed normally altho the organism was present and growing.

Plate IV. Results of Artificial Inoculation of Wheat with Wheat Scab Organism

Plate V. Results of Artificially Inoculating Various Plants with Wheat Scab Organism

Fig. A1 and A2. Stem rot of bean. Arrow indicates point of inoculation in diseased pot. Note stem punctures in check pot below (Fig. A2).

Fig. B1 and B2. Seedling blight of clover, two weeks after inoculation. Check pot on right.

Fig. C1 and C2. Stem rot of tomato, four days after inoculation. Arrows indicate points of inoculation in diseased pot. Check pot on right.

Fig. D1 and D2. Stem rot of cucumber. Arrows indicate points of inoculation in diseased pot. Check pot on right.

Fig. E. Potato tuber several weeks after inoculation.

Plate VI. Stem Rots Due to Wheat Scab Organism

Fig. A. Pea. Check pot on right.

Fig. B. Sunflower. The first and seventh pots from the left contain check plants; the soil of the third pot was inoculated with *Fusarium lini.*

Fig. C. Squash

Pot. 1, (a) Leaf petiole inoculated with *Fusarium lini.*
(b) Leaf petiole inoculated with wheat scab organism.
(c) Leaf petiole inoculated with wheat scab organism.
Pot 2, Stem inoculation
Pot 3, Check.

Plate VII. Root Rots Due to Wheat Scab Organism

Fig. A. Dry root-rot of bean. Plants on right inoculated with *Fusarium martii phaseoli,* the bean root-rot organism. Plants in the middle inoculated with wheat scab organism. Plants on left, checks.

Fig. B. Root-rot of corn. Plants on left inoculated with wheat scab organism, those on right, checks.

Plate VIII. Root-Rot of Corn Due to Wheat Scab Organism

Pot. 1, Soil inoculated.
Pot. 2, Check.
Pot 3, Check.
Pot. 4, Soil inoculated.

Plate IX. Effect of Treatment with Formaldehyde upon Development of Wheat Seedlings

Pot A, Healthy seed.
Pot B, Scabby seed, treated.
Pot C, Scabby seed, untreated.

PLATE I

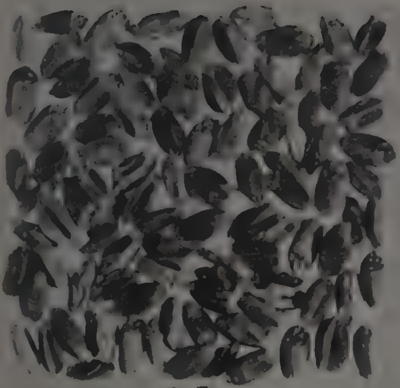


Fig. A_1

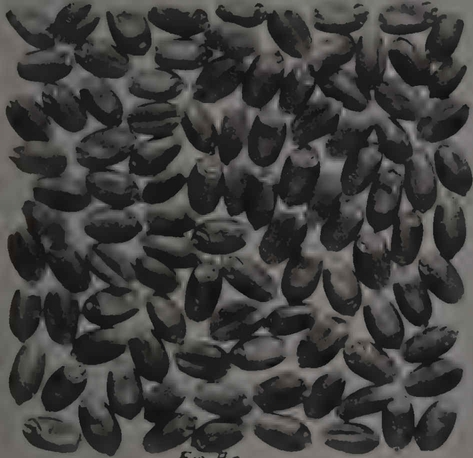


Fig. A_2

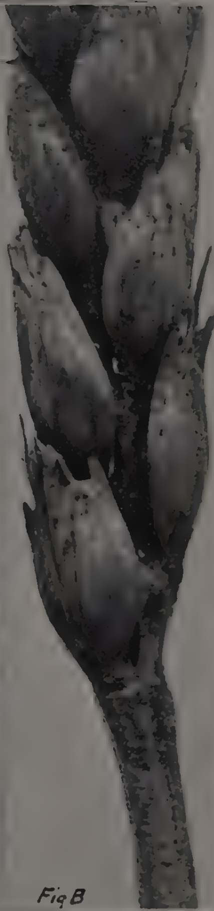


Fig B

PLATE II

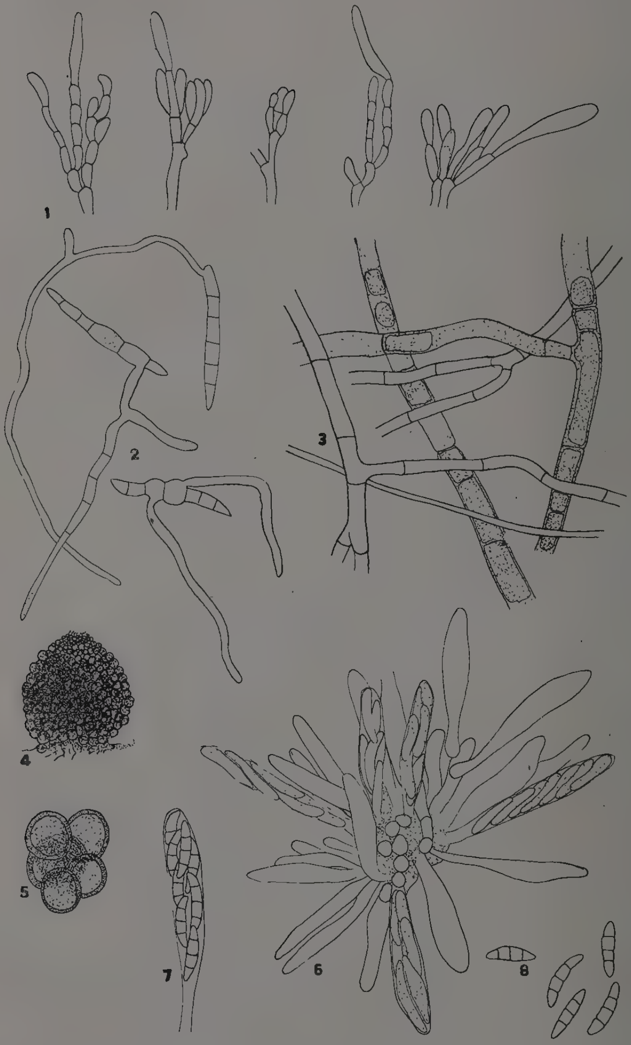
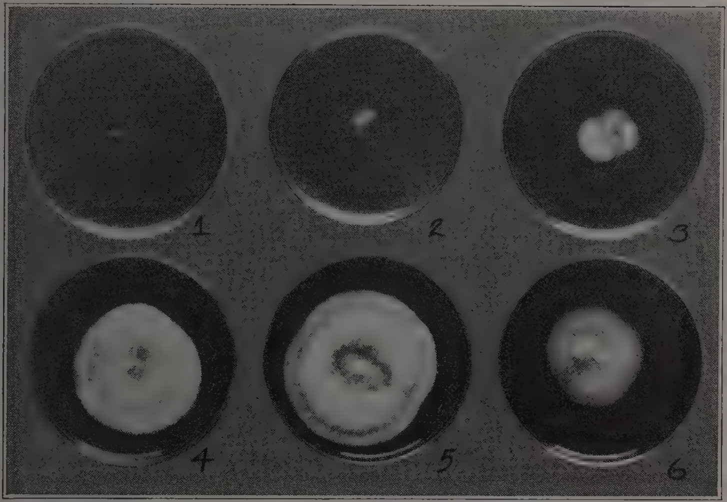


PLATE III

A



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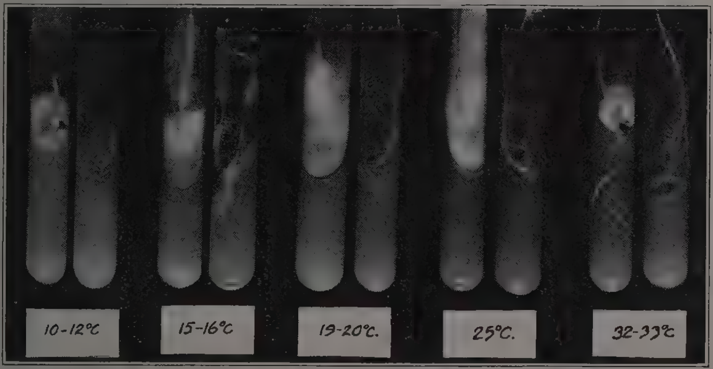

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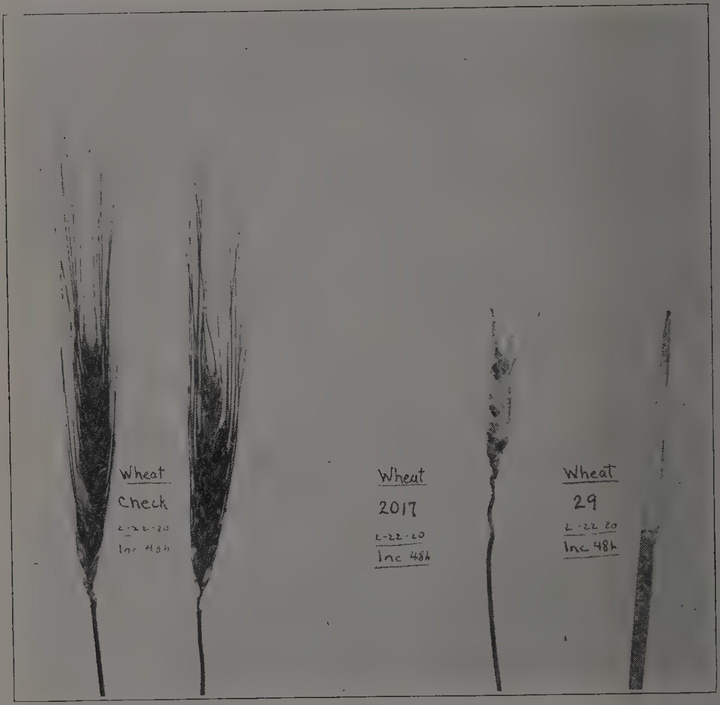

Wheat
Check
2-22-20
Inc 48h
Wheat
2017
2-22-20
Inc 48h
Wheat
29
2-22-20
Inc 48h

PLATE V

PLATE VI

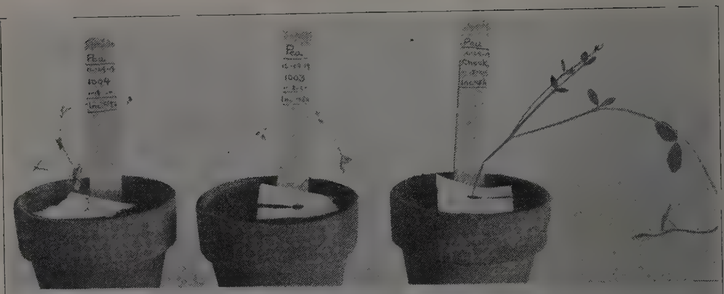


FIG A

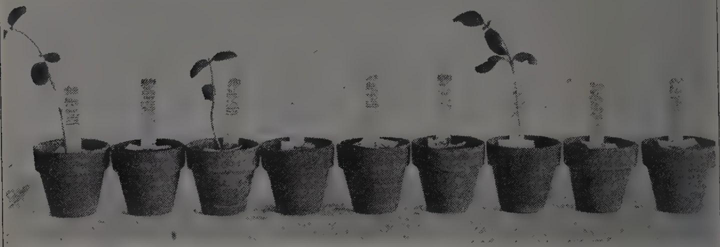


FIG B

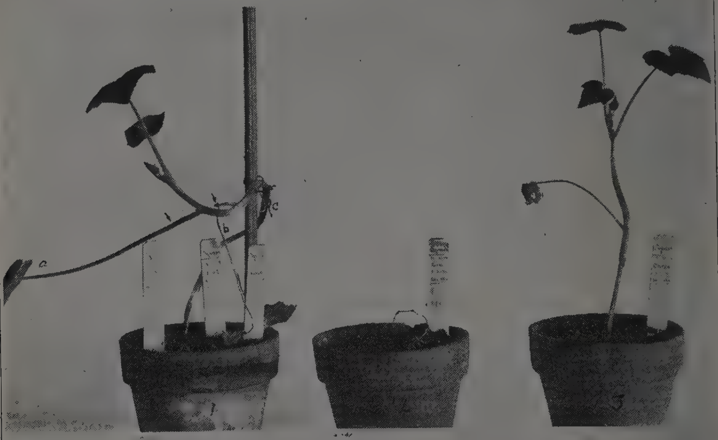
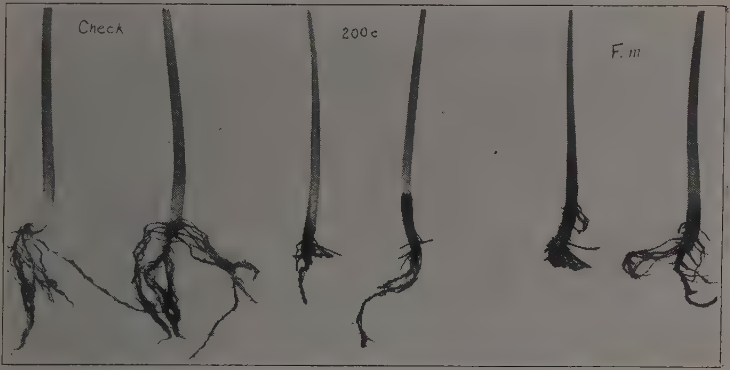


FIG C

PLATE VII

A



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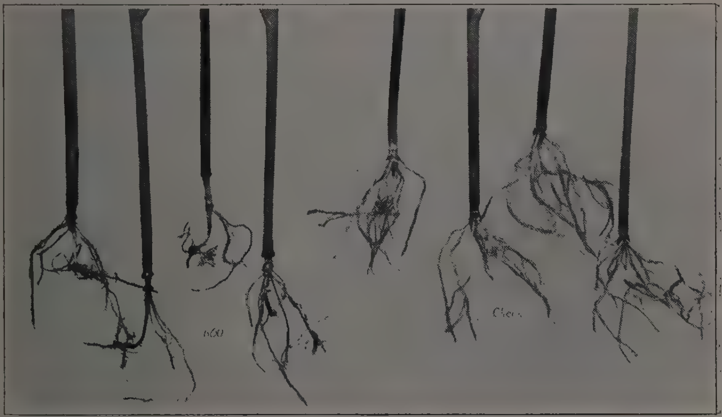


PLATE VIII

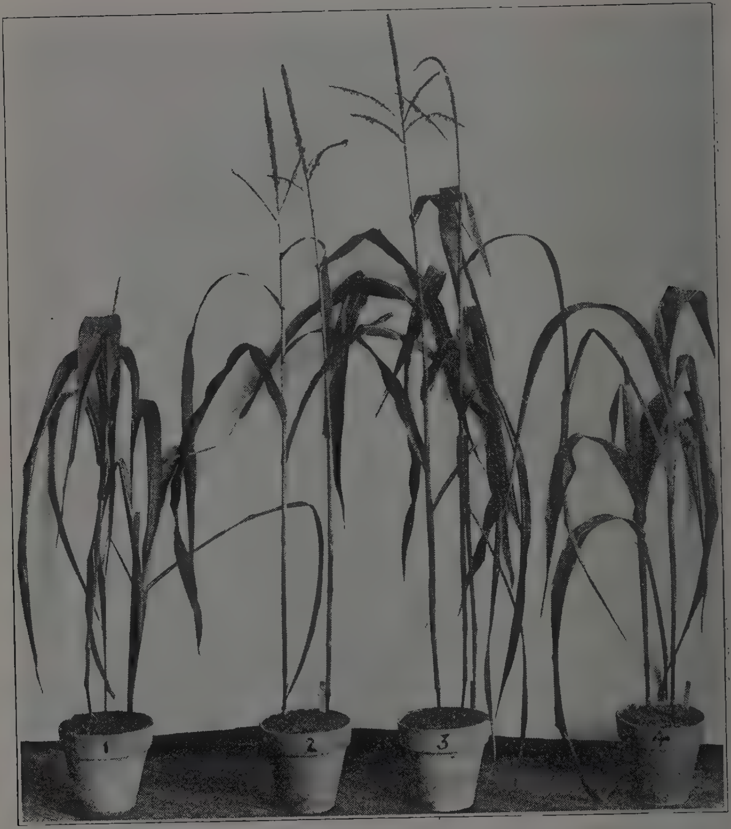
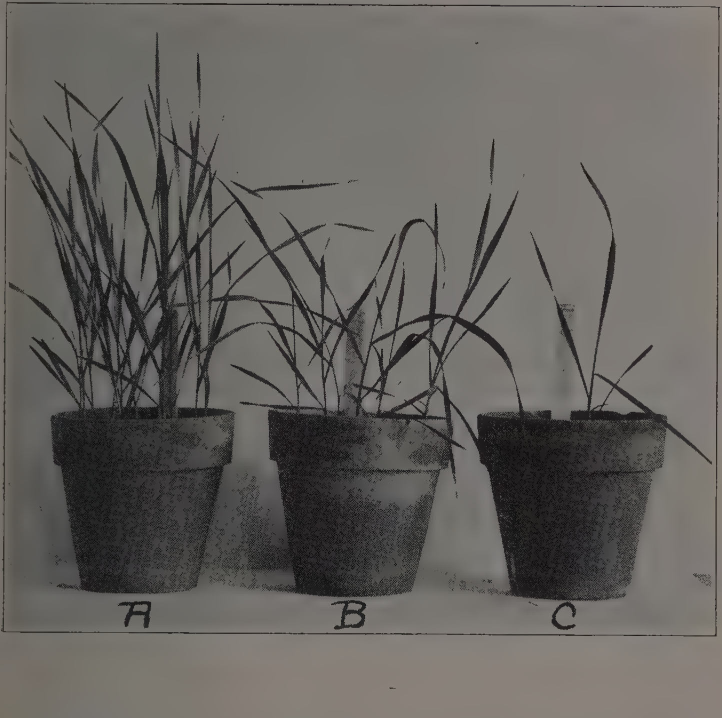


PLATE IX



TECHNICAL BULLETIN 19 OCTOBER 1923

The University of Minnesota
Agricultural Experiment Station

Viscosity as a Measure of Hydration Capacity of Wheat Flour and its Relation to Baking Strength

By Paul Francis Sharp with Ross Aiken Gortner
Division of Agricultural Biochemistry

UNIVERSITY FARM, ST. PAUL

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By Paul Francis Sharp with Ross Aiken Gortner
Division of Agricultural Biochemistry

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VISCOSITY AS A MEASURE OF HYDRATION CAPACITY OF WHEAT FLOUR AND ITS RELATION TO BAKING STRENGTH

By Paul Francis Sharp with Ross Aiken Gortner

INTRODUCTION

It has long been a matter of common knowledge that flours produced from different wheats vary in their baking qualities. Millers and bakers commonly designate flours of good baking qualities as "strong" and those of inferior baking qualities as "weak." The definition of "strength" found in the literature which is commonly accepted is that formulated by the English workers Humphries and Biffen (1907).

"A strong wheat is one which yields flour capable of making large well-piled loaves; the latter qualification thus excludes those wheats producing large loaves which do not rise satisfactorily."

Guthrie (1896) makes the following statement, altho his use of the term "strength" is not commonly employed.

"The property possessed by flour of absorbing water, known technically as the strength of the flour, is known to vary considerably in the different samples. In order to produce a dough of a given consistency, flour from different grain takes up quite different proportions of water. This is a factor of the greatest importance to the breadmaker, and consequently to the bread consumer, as well as to the miller and farmer, since upon it depends the volume and lightness of the baked loaf."

In England, Humphries has evolved a method of grading bread in which a numerical value called "bakers' mark" is assigned to the bread. Humphries (1908) states that in fifty or sixty cases he had awarded marks in the usual way and then measured the loaves. He found that the marks indicated the volume within a small percentage of error.

In the United States the volume of the loaf produced by a definite weight of flour when baked under a given set of conditions is usually taken as a measure of strength. Briggs (1913), in a discussion of the baking test, emphasizes the significance of loaf volume and points out that large volume of loaf and good texture are related. Thomas (1917), in addition to showing the relation of volume to strength, also pointed out that there was a correlation of strength with texture of the loaf as well.

As the volume of the loaf enters to a greater or less degree into all these definitions, the attempt was made in this work to use that as the main index of strength.

A certain correlation has been established between the strength of the flour yielded by different wheats and the geographical distribution of the wheats. Thomas (1917) summarized a great amount of data on this point. Soil, length of growing season, and moisture are probably the governing factors as indicated by many workers, notably Shutt (1909), Le Clerc and Leavitt (1910), Thatcher (1913), and Le Clerc and Yoder (1914).

Millers and bakers have long known that the wheats grown in the Northern Great Plains area of North America, that is, the spring wheat sections, produce flours having baking qualities superior to those grown in eastern, southern, and western regions. For this reason the geographical source of the wheat is often taken as an indication of the strength or weakness of the flour that can be milled from it. Owing to the overlapping of the regions in which the different types of wheat are grown, and to local and seasonal variations, the geographical source of the wheat in many instances gives only a rough approximation of the baking strength. The data presented by Thomas (1917) show this very clearly. Furthermore, certain varieties of wheat grown in the same geographical region yield flours of greater strength than others. The work of Biffin (1905-06) (1908-10), Thatcher (1913), Howard (1913) (1914), and others emphasized the importance of this factor, and as a result plant breeders have made a marked advance in increasing the strength of wheat grown in various regions by the introduction and development of new varieties and the elimination of undesirable types.

Baking tests are now used extensively in determining flour strength. Such tests are in many respects purely arbitrary procedures, and standardization of testing methods is to be desired. Various formulas are followed, and various treatments are accorded in the several testing laboratories. The skill of the baker also determines in large measure the characteristics of the test loaf. For these reasons it is impossible to compare the results of tests made in different laboratories unless they are all stated in terms of a common control sample, which is usually not the case.

While the procedure in measuring and scoring the test loaf is likewise variable, the comparative cubical dimensions (volume), and crumb texture of the loaf are commonly regarded as most significant. In estimating the latter the judgment of the operator is called into play, while the former may be measured with more or less precision and expressed in numerical values. For this reason loaf volume is most frequently employed as a criterion of flour strength.

Even tho an exact and standard method were available for conducting practical baking tests, it would still be necessary to regard the characteristics of the resultant loaves as the function of several variables. Thus the test might indicate any substantial deviation from the standard or type flour, without, of necessity, demonstrating the factor. Numerous workers have investigated almost every known chemical and physical property of flour that could possibly be correlated with strength. As yet all the limiting factors have not been discovered, or their inter-relationship recognized. The investigations reported in this paper constitute an effort to determine the significant properties of wheat gluten which may be correlated with baking strength.

HISTORICAL REVIEW

FLOUR STRENGTH

In the following discussion no attempt is made to review all the contributions to the literature on flour strength, but rather to review the more important factors which have been investigated by various workers in the attempt to throw light on the problem of flour strength.

Crude gluten.—Beccari (1745), professor of medicine, anatomy, and chemistry at the University of Bologna, was apparently the first to report the washing of crude gluten from flour with water. He says that he orally communicated to the Academy, in 1728, the fact that wheat flour can be separated into two parts, one of vegetable, the other of animal character.

Many investigators have attempted to correlate the amount of this crude gluten which a given flour will yield, with its baking strength. The process of determination, as ordinarily carried out, is to weigh out a definite quantity of flour, add enough water to form a dough, allow it to stand for some time, and then wash away the starch with water. The material remaining is called the wet gluten. It may be weighed and the results expressed in percentage of wet gluten on the basis of the original flour. The wet gluten is usually dried and the results are expressed in percentage of dry crude gluten on the basis of the original flour. The percentage of dry matter in the wet gluten is frequently calculated.

Millon (1854), while investigating the composition of wheat, pointed out the relationship between wet and dry gluten, and between dry gluten and the protein content of various flours.

As the different investigators began to use the amount of crude gluten as a measure of the baking properties of flour, they discovered many sources of error in the determination. Benard and Girardin (1881) found that the length of time the dough stood before washing out the gluten influenced the yield of gluten. Balland (1884) confirmed their results, showing in addition that the yield of gluten, as influenced by the time of standing, passed through a maximum. The time of reaching this maximum was found to vary with different flours. He showed that under the same conditions the percentage yield of gluten increased with the size of the sample of flour taken for the determination, also that between the limits of 40 to 60 grams of water per 100 grams of flour used in making the dough, the yield of gluten was the same altho harder to gather with the larger amounts of water. He found that hard wheat flour lost less gluten by continued washing than did soft wheat flour. Balland (1893) showed that the temperature at which the dough was made, allowed to stand, and washed, made a slight difference in the yield of gluten and that the ease with which it could be gathered and retained in the washing process varied. At a temperature of 2° C., he obtained from a given sample of flour 27 per cent of wet gluten; at 15° C., 27.6 per cent; and at 60° C., 30 per cent. Arpin (1902), reports results for the yield of dry gluten at the various temperatures showing an increase for a given flour. When washed at a temperature of 5° C., the yield of dry gluten was 7.83 per cent; at 15° C., 8.08 per cent; at 25° C., 8.24 per cent; and at 35° C., 8.46 per cent. He also showed that there was an increase in the yield of dry gluten of 4.7 per cent if hard water instead of distilled water was used in washing the gluten. Arpin also pointed out that moist gluten would take up additional water if allowed to stand in water, and that washing the material five minutes longer than the usual time decreased the percentage of both moist and dry gluten.

Balland (1884) (1893), Stein (1904), and others tried the effect of mixing various electrolytes with the dough and then washing out the gluten, and found that some electrolytes had little effect with normal flours and in many cases obtained no gluten.

Lindet and Ammann (1905) studied the effect of admixtures of lower grades of wheat flour on the washing out of the gluten from normal flours and in many cases obtained no gluten.

Fleurent (1905) recommends that distilled water containing 0.1 gram of calcium carbonate per liter be used in washing the starch from the flour for the first eleven minutes and that the gluten then be washed in distilled water for two minutes. He found that the same effect could not be obtained with calcium sulfate, calcium chloride, or sodium chloride, all three of these salts giving a lower yield of gluten. Olson (1912a) investigated the yield of gluten obtained when the original flour was doughed up with solutions of acids, bases, and salts. He found that the general effect was to decrease the yield. The solutions varied considerably in this respect. Upson and Calvin (1916) investigated the effect of washing out the gluten with carbon dioxide–free distilled water, tap water, various concentrations of sodium chloride, dibasic potassium phosphate, hydrochloric acid, and magnesium chloride. They came to the conclusion that carbon dioxide–free distilled water gave the best results. The influence of drying the crude gluten under various conditions was investigated by Neuman and Salecker (1908).

Macfarlane (1905) showed that crude gluten contained considerable other material in addition to protein. The amount of protein dissolved in washing out the gluten with water was determined. The gluten was then washed with 70 per cent alcohol, and the material dissolved by alcohol was determined by loss in weight and by nitrogen determinations of the alcohol extract, and finally the protein in the residue was determined.

Norton (1906), in his investigations of the protein content of crude gluten, found it to consist of only about 75 per cent gluten proteins, the range of protein content in the crude glutens which he investigated being from 68 to about 83 per cent. His results have been confirmed by many other workers. Norton also presented data which showed that the actual weight of the crude gluten varied from about 10 per cent less to over 17 per cent more than the total protein as shown by nitrogen determination on the flour. Olson (1912b) also investigated the composition of crude gluten. Kepner (1914) reviewed the various errors in washing out crude gluten.

We thus see that altho the influence of several factors on the crude gluten determination has been investigated, in many instances the workers arrived at diametrically opposite conclusions. Part of the difficulty may have been that each worker used a different type and grade of flour for his investigations. However, the results point out inherent sources of error in the quantitative determination itself.

While few investigators claim a direct parallelism between the quantity of crude gluten and the baking strength, Jago and Jago (1911) recommended the crude gluten determination and characterize it as follows:

"A gluten determination is an estimation of the amount of those bodies which are in such a physical condition as to impart elasticity and gas-retaining power to the dough at the time when the determination is made."

The principal suggestion of the above investigators regarding the crude gluten determination is that it should be made at the time the fermented loaf is ready for the oven. Balland (1896), while pointing out that gluten content of flours does not always parallel nitrogen content, nevertheless seems to believe that the gluten content tells the quality of the flour. Fleurent (1901a) points out that hard wheats are richer in gluten than soft wheats. König and Rintelen (1904) find no direct relationship between gluten content and strength. Norton (1906) and Neumann and Mohs (1910) come to the same conclusion.

Unable to find a direct relationship between gluten content and baking strength, Bremer (1907) and Schneidewind (1909) state that the baking strength of flour is dependent upon both quantity and quality of the gluten. Their opinion is shared by many other investigators, the difficulty being in determining the quality. It is the practice in most of the laboratories which make the crude gluten determination to report on both the quantity and the quality of the gluten obtained. The attempt at reporting its quality is usually confined to such descriptive words as tenacious, elastic, inelastic, soft, sticky, etc., the grading depending solely on the worker's judgment and memory.

There have been many attempts to vary the gluten content of a given flour and to compare the loaf volume produced. Snyder (1901) reports the addition of 10 and 20 per cent wheat starch to a given flour without decreasing the loaf volume, altho of course the proportion of gluten in the mixture was decreased. In another set of experiments Snyder washed enough starch from a flour to increase the gluten in one case 11 per cent and in another 25 per cent without materially changing the size of the loaf. Stein (1904) found that adding dry gluten to the extent of 7 per cent increased the volume of the loaf in one instance from 140 to 160 cubic centimeters and in another instance from 144 to 170 and 172 cubic centimeters. Stockham (1920) reports an increase in loaf volume due to addition of gluten. He does not state just how the increase in gluten content was brought about.

In this connection it is interesting to note that Olson (1911) at one time seemed to doubt the necessity of gluten in flour in order to make good bread.

Total protein.—While numerous investigators have shown that the comparison of individual flours for strength on a basis of their protein content is very unreliable, Shutt (1907) (1908) came to the conclusion that there is in general a relationship between baking strength and protein content. Roberts (1920), investigating the protein content of the variety types, finds some relation between type of wheat and protein content. Thomas (1917), in the comparison of total protein content with baking tests, showed clearly, taking the average of hundreds of determinations, an unmistakable relationship between loaf volume and protein content. It seems safe to conclude that taken as a whole there is a relationship between protein content and baking strength, but such a method of comparison is of little value when it is a question of comparing individual flours.

Gliadin-glutenin ratio.—To Einhof (1805) is attributed the discovery that wheat flour contained an alcohol-soluble protein which he considered the same as gluten. Taddei (1820) found that gluten consisted of two substances, one of which was soluble in alcohol. Since that time many investigations were carried out on the proteins of wheat gluten, namely those by Berzelius (1827), DeSaussure (1833), Boussingault (1837), Leibig (1841), Scherer (1841), Dumas and Cahours (1843), Mulder (1844), Günsberg (1862), Martin (1886), Fleurent (1893), O'Brien (1895), and Ritthausen (1896) (1899), but the most thoro and exhaustive work was that done by Osborne and Voorhees (1893), also Osborne (1907), Osborne and Harris (1905) (1906), and Osborne and Clapp (1906), who showed conclusively that true wheat gluten was composed of only two proteins, i.e., gliadin, soluble in medium concentrations of alcohol, and glutenin, insoluble in alcohol but soluble in dilute acids and alkalies.

No sooner had the identity of the proteins in the wheat gluten been established than investigations were carried out to ascertain the ratio of the two proteins in the glutens of strong and weak flours. Fleurent (1896a) (1896b) (1898a) (1898b) (1905) was one of the early workers to come to a conclusion on this point. He claimed that there was an optimum ratio of gliadin to glutenin of three to one, indicating a strong flour. If the ratio was greater or less than this optimum the flour was weak. He arrived at this conclusion by determining the ratio for different flours and by adding the protein necessary to correct this ratio and finding an improvement. Snyder (1897) (1899a) (1899b) (1901) came to the same conclusion with the exception that he thought the optimum ratio was 65 per cent of gliadin and 35 per cent of glutenin for greatest baking strength. He arrived at his conclusion in much the same way as did Fleurent. Snyder (1901) found that he could increase the gluten content from 11 to 25 per cent, the ratio of gliadin to glutenin remaining unaltered, without making an appreciable change in the volume of the loaf. This led him to the conclusion that it was not the quantity of gluten but the ratio of gliadin to glutenin that was the determining factor. Kosutány (1903) (1910) considers the gliadin-glutenin ratio of importance in determining the baking strength of flours.

Guess (1900) came to the conclusion that the quantity of the gluten as well as its quality as expressed by the gliadin-glutenin ratio was a factor in determining the strength of flour. He proposed that the gliadin-glutenin ratio be called the quality factor and that the actual quantity also be taken into consideration as a quantity factor. The product of the quality factor times the quantity of gluten represented the baking strength. Norton (1906) comes to nearly the same conclusion. König and Rintelen (1904), Wood (1907a) (1907b), Shutt (1909), Rammstedt (1909), and others came to the conclusion that the gliadin-glutenin ratio was not the determining factor in the strength of flour.

The gliadin-glutenin ratio has fallen into disrepute for another reason, namely, the difficulty of actually determining the true proportions of gliadin and glutenin as they exist in the flour. As early as 1862, Günsberg had shown that gliadin was appreciably soluble in water, and Teller (1896) found that gliadin was appreciably soluble in dilute salt solutions (as concentrated as 10 per cent). After making the corrections for the solubility of the gliadin in salt solution he concluded that gliadin and glutenin occur in the flour in approximately equal amounts. Chamberlain (1904) found that a large part of the water- and salt-soluble proteins were also dissolved in 70 per cent alcohol and would appear as gliadin. Olson (1913) confirmed Chamberlain's results and proposed distilling off the alcohol from the gliadin solution and concentrating to a small volume. This procedure coagulated out the gliadin, which was then filtered off and the amounts were determined, the coagulum being considered pure gliadin.

Bailey and Blish (1915) determined the amount of gliadin extracted from flours by means of water and salt solutions by taking advantage of the fact that the globulin and albumin of flour yield much less nitrogen in the ammonia fraction, when subjected to acid hydrolysis, than does gliadin. By a determination of the ammonia resulting from the acid hydrolysis of the proteins dissolved, they were able to determine the relative proportions of gliadin removed.

Gliadin content.—In addition to the use of the nitrogen determination for the estimation of gliadin, Fleurent (1901b) (1903) found that the gliadin content of a flour could be determined with sufficient accuracy by a determination of the density of an alcoholic solution; while Mathewson (1906a) thought that "the change in density in gliadin solutions for such differences as would be met with in flour analysis would allow rather a narrow limit for experimental error." Kjeldahl (1896), Osborne and Harris (1903), Snyder (1904), Marion (1906), Mathewson (1906b) (1908), Shaw (1907), Lindet and Ammann (1907), Thatcher (1907), Greaves (1911), and others investigated the use of the optical rotatory power of gliadin dissolved in alcohol as a means of its determination. Robertson and Greaves (1911) investigated the refractive index of gliadin in various solvents as a means of its determination. These methods of determination of gliadin in alcoholic solution have not attained very wide use.

While Greaves (1911) seems to conclude that pure gliadin reaches its maximum solubility in about 70 per cent alcohol, the percentage of protein extracted directly from flour by various concentrations of alcohol seems to go through a maximum at a concentration of alcohol of from 50 to 60 per cent as shown by Snyder (1906), Hoagland (1911), Schleimer (1911), Greaves (1911), Olson (1913), and others.

Chamberlain (1906), in attempting the separate analysis of the salt-soluble and alcohol-soluble proteins from the same sample of flour, confirmed his earlier work and that of Teller (1896)—that alcohol removed a large portion of the salt-soluble proteins. Chamberlain found in addition that if he extracted first with salt solution and subsequently with alcohol, he removed less protein than if he extracted in the reverse order. For example, in a given flour alcohol extracted 7.47 per cent protein, the subsequent extraction with salt solution removed 0.57 per cent in addition, or a total of 8.04 per cent removed by the two treatments. The direct extraction of the flour with salt solution removed 2.18 per cent and the subsequent extraction with alcohol removed 5.50 per cent, or a total of 7.68 per cent. His results point out still more strongly the difficulties encountered in a correct gliadin determination.

Most of the attempts to correlate gliadin content with strength have been based on the amount of protein extracted directly from the flour with 70 per cent alcohol. While König and Rintelen (1904), Norton (1906), Thatcher (1907), Wood (1907a), Rammstedt (1909), and Olson (1917) find no direct relationship between baking strength and gliadin content, nevertheless Norton believed that the best method at hand was the determination of the gliadin content together with the total protein content and the characteristics of the crude gluten, while Shutt (1907) (1909) thought that, in general, there was a relation between gliadin content and strength.

Fenyvessy (1911), attacking the problem in a somewhat different way, found that the loaf volume was increased by the addition of gliadin to flour. He found that rye gliadin would produce the same effect and that most of the added gliadin could be recovered in the crude hand-washed gluten.

Martin (1920) has recently carried out an investigation of some of the properties of wheat flour which he thought might be correlated with strength. He finds for the flours investigated that, "Flours with high gas-retaining capacity and high bakers' marks have been shown to be those in which the 'amended gliadin' figure is high, . . . for flours having a satisfactory gas-producing capacity, bakers' marks, gas-retaining capacity, and 'amended gliadin' content are closely related, and it is considered that the estimation of either of the latter together with the determination of the gas-producing capacity will indicate the strength of the flour." The amended gliadin figure as used by Martin was determined by subtracting from the percentage of protein extracted from a sample of flour in a Soxhlet extractor by means of 50 per cent alcohol, the percentage of protein extracted from 25 grams of flour by 250 cubic centimeters of water at 25° C., the time of extraction being three hours.

Glutenin content.—Guthrie (1896) has attributed the strength of flour to its glutenin content. He presents data showing that dried glutenin takes up about 78 per cent of its weight of water while dried gliadin takes up only about 40 per cent of its weight. It must be remembered that Guthrie considers the water absorbing capacity of a flour a measure of strength when he says:

"The strength or water absorbing capacity of a flour depends directly upon the relative proportion in which the two proteins are present in the gluten.

"If the gluten contents of two flours are nearly the same, that will be the stronger flour which contains the larger proportion of glutenin.

"Flours in which glutenin preponderates yield strong, tough, elastic, non-adhesive glutens.

"Increased gliadin content produces a weak, sticky, and inelastic gluten."

Woodman (1922), in a recent paper, concludes that the difference between a strong and a weak flour is due to a difference in the glutenin fraction. He bases his evidence on the optical behavior of the pure flour proteins when racemized at 37° with dilute alkali. He finds the gliadin from both types of flour to be identical, but the glutenins possess different optical rotations and when treated with alkali show different racemization curves. Woodman states, "The factor which determines the size of the loaf is most probably connected with the diastatic capacity of the flour as was suggested by this investigator (Wood, 1907a). On the other hand, the factor which determines the shape of the loaf and which appears to be directly related to the physical properties of the gluten of the flour, is possibly dependent on the particular glutenine mechanism possessed by the wheat. The results of this investigation suggest that the strong wheat synthesizes one type of glutenine and the weak wheat a different type." We shall have occasion to refer later to these views of Woodman in connection with our own experimental results.

Fenyvessy (1911) pointed out that the addition of glutenin to flour caused a deterioration in the baking qualities of the flour, altho most of the added protein could be recovered in the crude gluten determination. He was unable to obtain crude gluten from rye flour to which glutenin had been added. It perhaps might be mentioned here that Nasmuth (1903) stated that glutenin had a definite coagulation temperature of 70° C.

Water-soluble proteins.—While Bremer (1907), Shutt (1909), Rammstedt (1909), and Olson (1917) found no correlation between strength and water-soluble proteins, Rousseaux and Sirot (1913) (1918) believe that the strength of flour bears a direct relationship to the ratio of water-soluble protein to total protein. The ratio for good flours was found to be 1 to 5.72. The flours were considered weak if the ratio fell to 1 to 5.2. The ratio was found to be higher for the higher grades of flour. The ratio varied with the mill streams investigated. They report a ratio of 1 to 8 for a strong, glutenous American flour, and a ratio below 1 to 2 for a sample of flour that had been in storage for a long time.

As a point of interest in this connection, Humphries (1910) made the observation that the addition of a bran extract to the flour in the doughing process improved the quality of the loaf. This effect was later confirmed by White (1913), and Willard and Swanson (1913). Stockham (1920) showed that the water extract from the different grades of flour when used in making the dough for baking, causes an increase in the volume. He states:

"It may be seen that the extract from that grade having the greatest quantity of extract though the weakest when baked alone has the most accelerating and beneficial influence."

Chemical constitution of the proteins from strong and weak flours.—Wood (1907a) found that the amide nitrogen distribution was the same in the proteins of strong and weak flours. Gröh and Friedl (1914) found gliadin prepared from strong and weak flours to be identical in physical properties.

Blish (1916) subjected the individual proteins prepared from strong and weak flours to analysis by the Van Slyke method of amino acid fractionation, and came to the conclusion that as far as the Van Slyke method would show, the proteins from strong and weak flours were identical.

Sugar content.—While it is a well known fact that the sugar content of the flour will affect the resulting loaf in many cases (Wood, 1907a), and that the addition of sugar to flours which ordinarily give loaves of small volume will in many cases cause a great improvement, this phase of the problem will not be considered here, as Shutt

(1908) and others have shown that the sugar content is not the limiting factor and as the sugar content is usually corrected in the experimental baking, especially by the addition of sugar to the dough.

Fat content.—The effect of fat or shortening on the baking properties of wheat flour is a matter of common knowledge. Salmon (1908) found that if he extracted wheat flour with ether and then allowed the flour to dry spontaneously, the loaf made from it was much larger than was one made from the original flour. He also noted that the viscosity of the fatty matter varied within wide limits with the age and variety of the flour. Mohs (1915a) added increasing amounts of fats up to 10 per cent and found the volume of the loaf was increased, different fats varying in their ability to increase volume. Stockham (1920) found that extracting flour with ether caused a decrease in the volume of the loaf. He investigated the effect of adding 0.6 per cent of various fats and fatty acids and found that at this concentration wheat fat was the only one which caused a marked increase in the volume of the loaf while fatty acids all caused a decrease. He noted that the fat from a high-grade flour was relatively more solid than the fat from a low-grade flour. Saunders (1921) reports that the addition of about 3 per cent of lard increased the volume of the loaf on an average of 7 per cent. The effect of other fats and oils was studied.

Phosphorus content.—The relation of phosphorus content to strength has been investigated by many workers. White and Beard (1913), in their study of the problem, determined total phosphorus, organic phosphorus, inorganic phosphorus, and water-soluble phosphorus. They show that in general large loaves have less of all these groups of phosphorus. They concluded that the large loaves contained higher percentages of organic phosphorus than the smaller ones, the values for the larger being 93.5 per cent and for the smaller 87.3 per cent, altho the largest loaf contained only 85.8 per cent and the smallest 94.6 per cent.

Enzymes of wheat flour.—The diastatic enzymes of wheat flour have received much attention. Baker and Hulton (1908), Ford and Guthrie (1908), Swanson and Calvin (1913), and others have investigated their relation to strength. The results of investigations show that weakness in many instances is apparently due to a lack of sufficient diastatic power in the flour to supply the sugar necessary for proper fermentation. To correct this difficulty it is a common baking practice to add malt flours and extracts, and sugars. Koch (1914), as a result of his investigation, concluded that there was no difference in the amount of either diastase or invertase in strong and weak flours.

The proteolytic enzymes, while perhaps playing an important part in the strength of flour, are very difficult to study. Vines (1903) found considerable proteolytic activity in extracts of wheat germ. Proteolytic enzymes are present only in small amounts in flours, as shown by Baker and Hulton (1908), Ford and Guthrie (1908), Weaver and Wood (1920), Stockham (1920), and others. Stockham reports some very interesting experiments which indicate that the proteolytic enzymes found in flour come mainly from the germ. His results also show an increase in proteolytic enzyme activity as the grade of the flour decreases, and in flours made from sprouted wheat.

Gas-producing capacity.—Wood (1906-8) found for a series of flours with which he worked that the gas-producing capacity was closely related to bakers' marks, and believed that the determination of the gas-producing capacity gave an accurate indication of strength. The determination as first recommended by Wood was carried out by measuring over brine the amount of carbon dioxide evolved in 24 hours when 20 grams of flour was treated with yeast and water and incubated at 35° C. While this method has been used by Wood (1907a), Baker and Hulton (1908), Martin (1920), and many other workers, Alway and Hartzell (1909) concluded that the method was of little value. These authors found, in a series of tests extending over a month, in which the gas-producing capacity of the same flour was measured in duplicate 22 times, a difference amounting to as much as 170 per cent in the amount of carbon dioxide evolved in the first hour of fermentation and differences as great as 18 per cent at the end of 22 hours. These authors state:

"There is clearly no direct connection shown between the size of the loaf and the volume of gas evolved. The 13 flours which gave the largest loaves evolved on the average somewhat less gas than the other 13 flours."

Jago and Jago (1911), in their studies of the amount of gas evolved, used whole loaves and found that the strong flours evolved less gas than the weak ones. Stockham (1920) thinks that the amount of gas evolved is related to the grade of flour, the lower grades of flour as a rule evolving more carbon dioxide. The important relationship existing here has perhaps been expressed more clearly by Bailey (1916) when he says, "The strength of flour is determined by the ratio between the rate of production of CO_2 in and the rate of loss of CO_2 from, the fermenting mass of dough." He devised an automatic maximum reading expansimeter for measuring the maximum expansion attained by a given weight of flour in the form of a fermenting dough when treated exactly like another portion which was baked. His results show a close relation between the maximum expansion reached by the dough and the volume of the loaf produced. Bailey and Weigley (1922), working with a strong and a weak flour, investigated the rate of loss of carbon dioxide from doughs freshly made and from doughs which were normally fermented and ready to go into the oven. Their results show that the rate of loss of carbon dioxide is much greater from the weak-flour dough than from the strong-flour dough, the differences being especially marked in the doughs with no previous fermentation. The rate of expansion is correspondingly greater in the strong-flour dough as compared with the weak-flour dough. Fermented doughs expanded at a much more rapid rate than fresh doughs. To attain a given expansion of dough there was a much greater rate of loss of carbon dioxide from the weak-flour doughs than from the strong-flour doughs.

Hydrogen-ion concentration.—Jessen-Hansen (1911) was the first to point out the influence of the hydrogen-ion concentration on the volume of the loaf of bread produced from a given flour. He found the optimum concentration of hydrogen-ions for baking was approximately at a pH of 5 and that the volume of the loaf may be increased by the addition of acid if the pH without acid was greater than 5.0. In investigating the effect of flour improvers, he came to the conclusion that their effect was mainly to correct the hydrogen-ion concentration of the dough. As a result of the investigations of Jessen-Hansen, and of Cohn and Henderson (1918), Cohn, Wolbach, and Henderson (1918); Cohen, Cathcart, and Henderson (1918), and Henderson (1918) have devised a rapid method for the determination of the acidity of the baked loaf which consists in observing the color produced when a few drops of an alcoholic solution of methyl red are placed on the newly cut slice of bread. Morison and Collatz (1921) cast some doubt on the beneficial effect of acidity on loaf volume.

Mechanical strength testers.—Various mechanical testers have been devised for determining the baking value of flour. One of the first was the so-called "aleurometer" devised by Boland (1849) which consisted in measuring the volume that hand-washed gluten would attain when placed in a cylinder and heated in an oil bath. Kunitz (1885) recommends heating for 20 minutes at 200° C. Foster's gluten tester is an outgrowth of the aleurometer and measures the distance a plunger supporting a definite weight is moved by expanding gluten when baked. Sellnick (1899) devised a small apparatus which operated as an oven and was heated by a given quantity of alcohol in a prescribed manner. Doughs were made, using 20 grams of flour, 0.5 gram of sodium carbonate, 1 gram of acid potassium tartarate, and 18, 20, or 22 cc. of water, and baked immediately, the result giving the relative baking values of the flour. Liebermann (1901) baked the gluten washed from 20 grams of flour in a hollow capsule which he immersed in an oil bath heated to a temperature of 170° C., and from the volume of the baked gluten he determined the baking qualities of the flour.

Boland. Meyer, Kunis, and Kreusler also developed apparatus designed to determine the strength of gluten of small amounts of flour. The methods devised by these men and others are described by Maurizio (1902), who applied them to several flours. In this connection it is interesting to note that Mohs (1914) devised a mechanical gluten washer.

Wood (1912) used a turbidity method for determining strength. The flour was shaken with water for one hour and a solution of iodine in potassium iodide was added to an aliquot of the filtered extract and allowed to stand for one hour. The depth of the liquid through which an electric bulb could be seen was thought to be related to the strength of the flour. The greater the depth of liquid through which the bulb could be distinguished, the weaker the flour.

Hankóczy (1920) devised an apparatus by means of which a bubble of dough could be blown from a thin dough membrane. He thought baking strength was related to the volume of the bubble and to the pressure the bubble would maintain. Chopin (1921) described a similar apparatus by means of which he measured the tenacity of a dough by determining the maximum size of a bubble which could be blown from a given dough membrane. He found a direct relation between the square root of the volume of the bubble and the volume of loaf which a given flour would produce.

Cytology.—Miss Brenchley (1909) investigated the structure of the wheat kernel and its relation to strength. She concludes from her investigation that cytologically the wheat kernels that yield strong flours do not differ from those that yield weak flours.

Colloid chemical investigations of strength of wheat flours.—With the comparatively recent development of colloid chemistry, particularly the study of emulsoids, the attention of investigators on the subject of flour strength has been turned to the study of the colloidal factors that might influence the baking quality of flour.

Balland (1883) (1884), altho apparently not realizing the significance of his work from the colloid viewpoint, showed that gluten triturated with saturated sodium chloride lost some of its weight and attained the consistency of rubber. By washing in distilled water the gluten again took up the water which it had lost and attained its original weight, altho all the salt was not removed, as the ash was 2.8 grams, the ash of an untreated portion being 0.154 grams. He found solutions of the following salts to act similarly to sodium chloride, but with greater or less intensity: ammonium acetate, potassium carbonate, copper sulfate, iron sulfate, magnesium sulfate, zinc sulfate, alum, and glycerine. After immersion in 1-10 solutions of potassium bromide, potassium iodide, potassium nitrate; and 1-20 solutions of potassium chlorate and potassium borate; and in olive oil for 24 hours, the gluten did not appear to be modified. The gluten which was placed in the following solutions was attacked more or less and disappeared completely by washing in an excess of water: dilute nitric and hydrochloric acids, 1-10 citric and tartaric acids, dilute alcohol, dilute ammonia water, crystalline lead acetate, lead subacetate, and mercuric nitrate. He dried 100 grams of gluten in air and found that it lost 56 grams of water. In washing in water it took up all the water it lost and attained its original elastic properties. A similar sample dried at 100° C. lost 65 grams of water, but when washed in water it took up only a part of the water lost and its elastic properties had disappeared. Stein (1904) tried the effect on the yield of crude gluten of mixing various salts with the flour.

Wood (1907a) (1907b), Wood and Hardy (1908), and Hardy (1910) were the first to apply the methods used in the study of emulsoid colloids to the gluten from wheat flour. Hofmeister (1890) and many others had previously studied the effect of acids, bases, and salts on the imbibition of typical emulsoids.

Wood (1907b) extended these studies to the gluten from wheat flour. He was the first to attribute the differences between strong and weak flours to the colloidal properties of the proteins rather than to the chemical properties. This conclusion was reached only after a careful investigation of the chemical properties, as noted previously, such as: total nitrogen, total gliadin nitrogen, amide nitrogen in the gliadin, ratio of gliadin to total protein, total ash, acid, and carbon dioxide produced in the different flours.

In their study of the effect of acids, bases, and salts on the gluten, Wood (1907b) and Wood and Hardy (1908) suspended strings of gluten across V-shaped glass rods and immersed these strings of gluten in beakers containing the solutions that were being investigated. They found that if the gluten was suspended in distilled water it retained its coherence almost indefinitely, but if suspended in 0.001 normal hydrochloric acid, it immediately began to disperse, the rate of dispersion increasing as the concentration of the acid increased up to about 0.033 normal. As the concentration of acid increased from this point the dispersion rate decreased until the gluten finally became more coherent in 0.083 normal hydrochloric acid than it was originally. It was noticed that with sulfuric, phosphoric, and oxalic acids, dispersion took place even in high concentrations. Wood (1907b) also noticed that if salts were added to the acid solutions the effect of the acid was in a large measure counteracted. He concludes from his experiments that "the variations in coherence, elasticity, and water content observed in gluten extracted from different flours, are due rather to varying concentrations of acid and soluble salts in the natural surroundings of the gluten than to any intrinsic difference in the composition of the glutens themselves."

Olson (1912a) studied the effect of modifying the gluten environment of the flour on the crude gluten determination. The method he used was to dough up 10 grams of the flour with 6 cubic centimeters of the solution being studied. After standing for one hour the gluten was washed out with distilled water and the results were tabulated under the heads of percentage of gluten, weight of nitrogen in the gluten, percentage of nitrogen in the gluten, percentage of total nitrogen, and percentage of total nitrogen calculated from the nitrogen in the gluten from the original flour as 100.

These determinations were carried out with the original flour, with flour that had been made up into a dough and then dried and remilled, with flour that had been made up into a dough and then dialyzed for about three days with frequent changes of water and then dried and remilled, and finally with flour that had been stirred with a large volume of water and allowed to settle and the supernatant liquid decanted. After this process was repeated several times, the material was dried and remilled. He found that by mixing the untreated flour with 0.10 normal solutions of acids, salts, and alkalies the yield of gluten decreases, the effect being in the following order, sodium phosphate having the least effect: sodium phosphate, sodium chloride, magnesium sulfate, potassium phosphate, calcium phosphate, aluminum sulfate, sodium hydroxide, potassium hydroxide, sulfuric acid, phosphoric acid, and hydrochloric acid. It was found that the mere doughing up and drying process changed the character of the gluten to a small extent. The glutens that had been dialyzed showed marked differences from the original flour, the gluten yield being smaller. In the case of the decanted flour, it was almost impossible to collect the gluten, and values were obtained only in the case of sodium and potassium hydroxide, sodium sulfate, and magnesium sulfate. The gluten could not even be collected when treated with water only. Olson states that acids have a greater prejudicial effect than alkalies, and that of the alkalies, calcium hydroxide has a greater prejudicial effect than sodium or potassium. He concludes "there is as yet some unknown substance which is important in causing a transformation of the physical properties of the gluten."

Gröh and Friedl (1914) made a careful study of the physical properties of gliadin separated from strong and weak flours. They studied the following physico-chemical properties of gliadin solutions of the different flours in potassium hydroxide: viscosity, surface tension, specific rotation, gold number, refractive index, and the time it took a platinum sol to which a given amount of gliadin had been added, to decompose half of a known amount of hydrogen peroxide. They separated the alcohol-soluble protein of flour into four fractions and found them all to be the same within experimental error except the first, which was shown to contain impurities. They show that the above physical constants of the gliadins separated from four flours of different strengths are the same. They conclude that the differences in strength are colloid-chemical and that these differences are changed either by the extraction with alcohol or by the treatment with potassium hydroxide. They obtained from rye an alcohol-soluble fraction which appeared to be identical with wheat gliadin in the above mentioned physico-chemical properties.

Upson and Calvin (1915) (1916) studied the imbibition of gluten as influenced by acids, and acids in the presence of salts. A more exact method was used than that of Wood and Hardy. The gluten was washed from flour and pressed into sheets from which discs were cut with a large cork borer. The discs were then weighed and placed in the various solutions for a given period of time, when they were removed and again weighed. The results were calculated on the basis of increase in grams per gram of moist gluten. They confirmed the findings of Wood and Hardy, finding the greatest imbibition in the case of hydrochloric acid at moderate concentrations (0.01 normal), while with high concentrations (0.2 to 0.5 normal), the solutions actually removed water from the gluten. They found that with lactic and acetic acids this effect was not so marked at the higher concentrations, in the case of the lactic acid the swelling being almost as great in 0.5 normal as in 0.005 normal solutions. They also found that in the presence of acid plus various salts the swelling decreased almost in proportion to the amount of added salt. They also demonstrated the reversibility of the action. Discs that had more than doubled in weight after remaining in acetic acid for two hours, not only resumed their original weight but also their original appearance and physical properties of toughness and elasticity, when placed in 0.1 normal dipotassium phosphate for one hour. Upson and Calvin (1916) conclude "that the bread making qualities of dough made from wheat flour are dependent on the quantity and quality of the contained gluten. Quality of gluten is regulated by the kind and concentration of the acids and salts present in the dough. If the kind and amount of acids and salts are such as to favor water absorption, the quality of the gluten will be poor, whereas the presence of acids and salts in such amounts as to tend to inhibit water absorption makes for an improved gluten."

Gortner and Doherty (1918) applied the method used by Upson and Calvin to gluten separated from flours of different strengths. The other workers in this field had worked with only one type of gluten and had drawn conclusions for the other types. Gortner and Doherty found that glutens from strong flours had a greater rate of imbibition than glutens from weak flours. This difference was noted in solutions of hydrochloric, acetic, lactic, orthophosphoric, and oxalic acids. They tried the effect on the swelling rate of five different glutens in various concentrations of these acids alone; and in the case of three of the glutens, the effect of hydrochloric and lactic acids in the presence of 0.005 molar solutions of potassium chloride, potassium phosphate, potassium tartrate, calcium chloride, mercuric chloride, aluminum sulfate, and magnesium sulfate; and in addition the effect of the last named three salts on swelling with oxalic and acetic acids. While the effect of the addition of salts to the various acids was to decrease the imbibitional rate, the ratio of the effect on the strong and weak glutens remained about the same, that is, the strong flour glutens still had a higher rate of imbibition than the weak flour glutens. This is the first instance in which a marked difference in physico-chemical properties has been found between the glutens from strong and weak flours, except, of course, in the general appearance of the gluten. Gortner and Doherty show that their results refute the conclusions of Upson and Calvin regarding flour strength in that the crude glutens investigated by both Gortner and Doherty and by Upson and Calvin contained almost the same amount of moisture. This would not be the case if the conclusion of Upson and Calvin were true. The differences in imbibitional power shown by the glutens that Gortner and Doherty used are so great that they could not possibly be correlated with the original moisture content of the wet gluten. These authors show that in addition to a marked difference in the rate of imbibition, there is a marked difference in the maximum hydration capacity, the weak-flour gluten dispersing much sooner and at a much lower water content than the strong-flour gluten. These results also refute the contention of Wood and Hardy (1908) that the difference between them is due to the strength of the electric double layer. If this were true the glutens would all have the same imbibitional rate but it would be found in different concentrations of acid.

Gortner and Doherty conclude that the glutens are different even at the isoelectric point and that, "the difference between a strong and weak gluten is apparently that between a nearly perfect colloidal gel with highly pronounced physico-chemical properties, such as pertain to emulsoids, and that of a colloidal gel in which the properties are much less marked. It is suggested that such differences may be due to the size of the gluten particles and that at least a part of the particles comprising the weak gluten may lie nearer the boundary between the colloidal and crystalloidal states of matter than is the case with the stronger glutens."

Henderson, Fenn, and Cohn (1919) report some very interesting studies of the effect of electrolytes on the viscosity of dough. The method used was to prepare a dough from a given flour, using a constant volume of water or solution. Twelve grams of this dough were placed in a small chamber with pins protruding from the bottom to hold the dough firmly, a paddle wheel was thrust into the dough and rotated by means of a weight on the end of a string which passed over a pulley, and the time taken for this weight to move through a distance of 2 meters was used to indicate the viscosity of the dough. In studying the effect of hydrogen-ion concentration, it was found that the viscosity of the dough passed through a minimum occurring at approximately a pH of 4.7. By adding increasing concentrations of sodium chloride to the dough the viscosity first fell and then rose to above its original value. Magnesium sulfate caused a greater fall over a longer range of concentration and a slight rise at the higher concentrations. The effect of various concentrations of sodium chloride at a pH of 5.8 and of 4.8 was investigated. The viscosity fell more at 4.8 and the rise in the higher concentrations of salt was very slight. By using a constant quantity of the various salts and varying the hydrogen-ion concentration, the minimum viscosity values were found at widely different hydrogen-ion concentrations. The minimum with sodium chloride was found at a pH of about 3.8, while with calcium chloride the minimum was at 5.8. The authors state, "It is advantageous to employ a dough of relatively low viscosity or, speaking more correctly, to reduce whatever quantity of gluten may be present to a condition in which the viscosity is low."

In a later paper Henderson, Cohn, Cathcart, Wachman, and Fenn (1919) report some of the results of their study on the conductivity, hydrogen-ion concentrations, and binding power of gluten in the presence of acid or alkali. These authors conclude, "The results seem to show that simple chemical phenomena are most important in such systems and that the modification of these resulting from colloidal and heterogeneous characteristics are of secondary importance in determining the condition of equilibrium tho somewhat significant in the progress of the system toward the condition of equilibrium."

Mohs (1915b), in a general theoretical discussion, points out the importance of the different phases, especially the relationship of the surface involved and the resulting power of adsorption. He emphasizes particularly the behavior of gliadin as a protective colloid. He explained that the gluten in the dough is in the gel state, in the flour it was said to be present in a more dehydrated form, while if the flour was heated the gluten was irreversibly coagulated and would not again take up water to form gluten.

Ostwald (1919), Lüers (1919), and Lüers and Ostwald (1919) (1920a) (1920b) investigated the problem of bread making from the colloid standpoint. Ostwald (1919), in the first paper of the series, gave a general discussion of the bread baking process from the colloid viewpoint. He said that flour is a coarse dispersion of several poor-in-water hydrogels, such as protein gel, carbohydrate gel, the starch grains, and cellulose gel of the cell walls (crude fiber). There are also present the molecularly dispersed substances, salts, sugar, acid, and especially water, also gases not only dissolved but adsorbed on the surface. The dough is described as a polydisperse system where water is the dispersion medium in which dextrin, sugar, alcohol, and especially salts, acids, and gases are molecularly dispersed, the dissolved plant albumin, swollen starch grains, and finer gas bubbles are colloidally dispersed, and finally the yeast cells and lactic acid bacteria make up the coarse dispersed part. The dough has a combination of the properties of a solid and a liquid. In the baking process the starch becomes gelatinized and the protein coagulated, the carbon dioxide and some of the water are driven from the molecular dispersion over into a gas dispersion which becomes fixed in the gel sponge structure of the bread. Ostwald suggests that the staling of bread might be due to syneresis. He also points out many lines of investigation in which viscosity determinations under certain conditions would throw light on the problem of bread baking.

Lüers and Ostwald (1919), in the second paper of the series, began a study of the viscosity of the flour paste made by heating the flour with water at 100° C. They considered that there were two great regions offered for viscosity study, the one which has to do with dough formation and the other with dough baking. They believed the properties making for a good dough and those making for good baking conditions are distinct. The method used in preparation of the flour pastes was first to dough up the accurately weighed amount of flour with small amounts of water, finally adding a total of 10 cc. This material was poured into 100 cc. of boiling water and heated one minute, and then filtered through muslin into a tared 500 cc. Erlenmeyer flask, washed, and made up to a weight of 200 grams, closed with a stopper carrying a capillary tube, placed in a boiling water bath for half an hour, cooled to 20° C., and the viscosity determined in an Ostwald capillary viscosimeter. The viscosimeter used had a capacity of about 10 cc. and the time of outflow for water was about two minutes.

Using this method it was found that boiling from half an hour to two hours decreased the time of outflow from 1098 to 1079 fifths of seconds. When working with the lower concentrations it was found that if a more concentrated solution was first made up and then diluted the readings were much higher than if the more dilute solution was made up directly. The viscosity of the diluted solution eventually fell to a value nearly the same as the one made up directly without previous dilution. The explanation offered for this phenomenon is that in more concentrated flour pastes larger particles are present and the dilution causes an increase in the degree of dispersion. In an investigation of the different grades of flour, these authors found the viscosity of flour pastes divided themselves into three classes; the patent flours showed a greater viscosity than the straight flours, while the first clear flour showed the least viscosity. This was found to hold for both the wheat and the rye flours investigated. They concluded that the viscosity of the flour pastes was directly proportional to the starch content and suggested that the viscosity of the starch pastes might be used as a method of measuring the starch content of flours. It was found that the addition of increasing concentrations of sulfuric acid caused an increase in viscosity amounting to from 7 to 9 per cent, followed by a fall in viscosity. They attribute this effect to the protein present and not to the starch, since Samec (1912) (1914) and Samec and von Hoefft (1913) have shown acids to have the reverse effect on pure starch pastes.

In the measurement of the viscosity of the dough solutions, Lüers and Ostwald used a viscosimeter of the Ostwald type having a capillary 3.5 millimeters in diameter and a capacity of about 20 cc. The time of outflow for water was 24 fifths of seconds. The dough solutions were prepared by adding to the flour one and one-half times its weight of water and stirring to a paste, then adding water from a burette until the desired amount had been added. These authors investigated solutions ranging in concentration from 7 to 20 per cent flour. They found that rye flours of the same grade and concentration gave relatively much more viscous solutions than did wheat flours, and this is suggested as a method of differentiating the two. With wheat flour the lower the grade the more viscous was the solution, just the reverse of the behavior of the flour pastes prepared by heating the flour in water. With rye flours, the same rule holds except that the clear and the 94 per cent flour both showed a low viscosity.

They attribute this to the presence of more of the proteins from the aleurone layer which they think have a depressing effect on the viscosity. It was found that the viscosity of the wheat flour solutions decreased with time except in the 40 per cent patent in a flour-water suspension of 13.05 per cent (the highest investigated) in which there was a slight increase followed by a decrease. With rye flours, however, there was an increase with time of standing in all cases amounting to 13 per cent in the 40 per cent rye patent in a flour-water suspension of 13.05 per cent, the highest investigated. They were unable to find in the literature any instance in which this after-swelling had been taken into consideration.

The investigation which these authors carried out on the effect of various concentrations of lactic acid on the rye and wheat flours of different grades is so interesting that some of their data are grouped in Table I.

TABLE I

Effect of 0.050 Normal Solutions of Lactic Acid on Relative Viscosity (Water Taken as Unity) of 20% Solutions of Wheat Flour of Different Grades and of 0.015 Normal Solution of Lactic Acid on 6.98% Solutions of Rye Flours of Different Grades. Temperature 20° C.[*][†]

Mill grade per cent extraction	20 per cent wheat flour solutions		6.98 per cent rye flour solutions	
	Viscosity in water	Viscosity in 0.050 N lactic acid	Viscosity in water	Viscosity in 0.015 N lactic acid
0-40	3.54	16.16	2.17	2.00
0-60	4.24	22.29	3.33	3.02
0-75	4.54	11.04	3.96	3.88
0-90	4.71	7.67	4.38	4.08
0-94	5.13	7.70	2.88	2.64
60-90 clear	9.67	9.79	2.29	2.13

[*] Data taken from work of Lüers and Ostwald (Kolloid Z. Bd. 25, S. 126-127).

[†] Intermediate concentrations were also investigated but the differences are most apparent in the values selected for this table. In the case of the 75% rye flour, a rise to 4.46 was found in lactic acid of 0.0038 normality.

With wheat flours, except the 40 per cent patent, the effect of acid in increasing the viscosity diminishes as the grade decreases. One of the most striking results of this study is the difference in effect of lactic acid on the rye and the wheat flours. Acid seems to have relatively no effect in increasing the viscosity of rye flour solutions.

These authors investigated the hydrogen-ion concentration of the solution filtered from 7.5 per cent dough solutions of various grades of flour when made up with water and when made up with 0.0038 normal lactic acid, and found that the higher the grade the more acid was the water solution, also the higher the grade the more acid was the lactic acid solution. The actual hydrogen-ion concentration of the water extract of rye and wheat flours of the same grade was nearly the same. The spread of the difference of hydrogen-ion concentration between water and lactic acid solutions decreased with the grade. A more thoro study of this point has been carried out by Bailey and Peterson (1921) who found a close relationship between the buffer value of the water extract and the grade of the flour, the lower grades having the greatest buffer value.

Lüers and Ostwald studied the effect of sodium chloride on the viscosity of the different grades of flour and found that it decreased the viscosity. In their study of the effect of the various hard waters they found that some of them raised the viscosity while others lowered it. In one instance a weak rye flour of 94 per cent extraction was compared in viscosity with the 94 per cent rye flour previously used and was found to have only about two-thirds the viscosity of the latter. It was found that the addition of salt to the concentration used did not decrease the viscosity of the weak flour.

In the third paper of this series, Lüers (1919) took up a study of the gliadin prepared from wheat and rye flours. He studied the effect of acids, bases, and salts on the viscosity of gliadin sols. In each experiment, 15 cc. of carbon dioxide-free distilled water was placed in the viscosimeter and 2 cc. of an alcohol solution of gliadin of a known concentration was added. The outlet tubes of the viscosimeter were protected from carbon dioxide with soda lime tubes, and air was blown through the apparatus to stir the solution. The effect of the electrolyte being studied was carried out by adding small amounts of a concentrated solution to the material already in the viscosimeter, corrections being made for the dilution. The reason for guarding against carbon dioxide was that he found gliadin to be precipitated by the trace of carbon dioxide ordinarily present in the distilled water. Gliadin was, however, found to dissolve in water saturated with carbon dioxide. It was found that as increasing amounts of hydrochloric acid were added the viscosity of the gliadin solution decreased slightly, then increased to a maximum and again fell to nearly its original value. With sodium hydroxide the viscosity rose to a maximum and remained near the maximum point as far as investigated. The maximum for the sodium hydroxide was not nearly so high as for the hydrochloric acid. It was found that hydrochloric, sulfuric, and lactic acids at low concentrations all precipitated gliadin. The increase in viscosity produced by increasing concentrations of sulfuric acid was not great and gliadin was precipitated at the higher concentrations. Lactic acid caused a greater rise in viscosity than did sulfuric acid and produced only a slight turbidity at the higher concentrations. The maximum viscosity for hydrochloric acid occurred at a normality of 0.0004 for wheat, and 0.00066 for rye gliadin. The maximum viscosity obtained with sulfuric acid occurred at a concentration of 0.0022 normal for both wheat and rye gliadin. With lactic acid the values were 0.018 and 0.011 normal. With sodium hydroxide the maximum was found to be at 0.0022 normal for both, while the maximum for the wheat gliadin in barium hydroxide was at 0.013 normal and for rye gliadin 0.014 normal.

Salt solutions were found to have a depressing effect on the viscosity in the presence of lactic acid. Hydrochloric acid was found to have a marked increasing effect on the viscosity of the gliadin when dissolved in 71.5 and 42.6 per cent alcohol. The viscosity in each case passed through a maximum at 0.0015 normal hydrochloric acid. It was shown that the viscosity increased with rise in temperature. Diluting the gliadin solution with water caused an increase in viscosity, but if 0.05 cc. of 0.5 normal hydrochloric acid had been added previously, the viscosity decreased with dilution. The author explained the rise in the first instance as being due to dilution of the alcohol which permitted a hydration of the gliadin by water, while with hydrochloric acid of the concentration mentioned no hydration could take place. In all the experiments reported, no essential difference was noted between the gliadin from wheat and that from rye and the author concluded that they were identical. This confirms the earlier conclusions of Gröh and Friedl (1914).

Lüers reported the results of three cataphoresis experiments. At a pH of 9.05 the gliadin migrated to the anode, at 6.70 there was no apparent migration, and at 5.98 the migration was to the cathode. The coagulation optimum was found near a pH of 6.15. He concluded that the isoelectric point of gliadin is near the neutral point. Rona and Michaelis (1910) found the isoelectric point of gliadin to be at a hydrogen-ion concentration of 6.0×10^{-10} or a pH of approximately 9.2. Lüers found that gliadin bound more base than acid. The author concluded that the hydrosol of gliadin was a suspensoid because it was so sensitive to electrolytes, while in alcohol gliadin was an emulsoid. He found the precipitate obtained at the isoelectric point was different in character from the precipitate obtained in high concentrations of acid. He considered that gliadin would be in a slightly swollen condition at a pH of 5.0, which Jessen-Hansen (1911) had shown to be the optimum for bread making. Lüers seemed to consider gliadin the most important colloid of the gluten and emphasized its value as a protective colloid, yet he mentioned that glutenin must also play an important part.

In the fourth paper, Lüers and Ostwald (1920a) reported the study of the viscosity of two weak rye flours. They found that one has about one-fourth the viscosity of the normal rye flour of the same grade. It is emphasized that the best flour should probably show a medium viscosity, neither too high nor too low.

In a fifth paper, Lüers and Ostwald (1920b) discuss the work of Upson and Calvin (1916). They state that their conclusions are in essential agreement. While both emphasize that it is the quality and not the quantity of the gluten which is important, they seem to think that the quality is regulated by the acids and salts present in the flour, or those added to it.

In a later paper, Lüers and Schneider (1921) discuss the methods of measurement of the swelling of colloids as applied to the proteins of flour. They found that by using the viscosity and sedimentation method as affected by acid and alkali they obtained results which when expressed graphically gave curves similar to the ones obtained by Upson and Calvin (1916) for the swelling of gluten discs by the weight method. These curves were also similar to the ones obtained by Lüers (1919) for the viscosity of gliadin. They conclude that all three methods accomplish the desired object.

Whymper (1920) emphasizes the importance of the starch in the colloid chemistry of bread making.

Stockham (1920) determined the concentration of various salts necessary to overcome the dispersing effect on gluten of several acids in different concentrations. He also states ,"Gluten may easily be obtained in a coherent form from the dispersed state but attempts to secure gluten in this manner identical in properties with the original were not satisfactory."

Sharp and Gortner (1922) in a continuation of work along the line begun by Gortner and Doherty (1918) found, in a study of the imbibitional properties of the glutens from four different flours, that the strong flour gluten had a much higher rate of imbibition than the weak flour gluten. Sharp and Gortner found this difference in rate held in solutions of various concentrations of hydrochloric acid, lactic acid, and potassium, sodium, barium, calcium, and ammonium hydroxides. They conclude that the presence of salts decreases the imbibition in alkalies in somewhat the same manner as in acids. They find the reaction of glutens in alkalies to be somewhat different from the reaction of the glutens to acids, dispersion taking place much more rapidly and at lower concentrations in the case of alkalies.

They state, "Drying the glutens washed from the different flours in a vacuum oven at 45-50° C. markedly altered the physico-chemical properties of the glutens, the properties of the different glutens studied becoming more nearly alike. This conclusion is in complete accord with the theory that the strong gluten is strong because of more pronounced colloidal properties, inasmuch as it is well known that alternately wetting and drying a colloidal gel breaks down the gel structure."

Sharp and Gortner present evidence tending to show that the optimum hydrogen-ion concentration for the imbibition of discs of gluten is the same for the various acids. They conclude that their findings are in complete accord with the earlier postulate of Gortner and Doherty (1918).

Mohs (1922) makes a three-fold division of the water content of the gluten of flour: (1) The lowest, which is found in flour that has been heated; (2) that which is found in normal flour (in this division the "hard" wheat gluten contains less water than the "weak" wheat gluten); (3) that obtained when flour is mixed with water (in this division the weaker the flour the greater the quantity of water absorbed by the gluten). This representation is in close agreement with the explanations of Upson and Calvin (1916) who in addition believe that a special combination of electrolytes causes the gluten to take up more water and thus behave as a weak gluten. Gortner and Doherty (1918) did not agree with the explanations of Upson and Calvin.

Mohs thought that the gluten particles of the strongest flours adsorbed the water on their surfaces but that no water penetrated them. Such flours were too strong. In the case of the normal flour it was explained that part of the water was adsorbed on the surface and part entered the gluten particles, causing them to swell; while with the weak flour gluten the water all entered the particles with none or relatively little on the outer surface, and this hydration of the interior had a great tendency to cause the disintegration of the particles.

This review of the main lines of investigation on flour strength seems to indicate that the greatest advance toward a solution of the problem has been made in the investigation of the colloidal properties of flour.

In taking up a further study of the colloidal properties of the strong and weak flours, the method previously used by Sharp and Gortner (1922) and others, of washing out the glutens and studying their imbibitional rates, was abandoned for the much simpler procedure used by Lüers and Ostwald (1919), which consisted essentially in determining the viscosity of a flour-in-water suspension.

Sharp and Gortner (1919) had found that when glutens were dissolved in various concentrations of potassium hydroxide the gluten from a strong flour exhibited a greater viscosity than that from a weak flour. The concentration of dispersed gluten was ascertained by means of a Kjeldahl determination on an aliquot of the potassium hydroxide solution.

VISCOSITY OF COLLOIDAL SYSTEMS

In the following discussion no attempt is made to review all the literature on the viscosity of colloids. The discussion is intended rather to indicate the special applications of viscosity measurements to colloidal systems, and to show how viscosity measurements have bene made to serve as an index to the changes taking place in such systems.

Coefficient of viscosity.—The coefficient of viscosity in the centimeter, gram, second system may be defined as that force which when exerted on unit area between two parallel planes of unit area placed one centimeter apart would produce a difference in the velocity of streaming of the two planes of one centimeter per second. The reciprocal of the viscosity is called the fluidity.

It was suggested by Deeley and Parr (1913) and later recommended by Bingham and Jackson (1917) that the unit of viscosity be called the "poise" to commemorate Poiseuille's pioneer work in the field of viscosity studies. It is also convenient to use the sub-multiple of this unit which therefore is called the "centipoise." It so happens that one centipoise is almost exactly the absolute viscosity of water at 20° C. The value given by Bingham and Jackson (1917) is 1.0050 centipoise.

Methods of measurement.—The methods used for the measurement of viscosity are modifications of a few general types. The two types used in this investigation will be discussed in some detail. The first of these is the method studied first by Poiseuille (1847), who developed from the results of his measurements the equation for the flow of a liquid through small capillary tubes. The equation as developed by Poiseuille was

$$V = K \frac{p\,D^4\,t}{l}$$

in which V was the volume of the liquid which flowed in the time t, through a capillary whose length was l and whose diameter was D, p being the pressure causing the flow and K being a constant. This equation was developed further by Hagenbach (1860) who expressed the relationship in the following form:

$$\eta = \frac{\pi\,r^4\,p\,t}{8\,l\,V}$$

Where η is the coefficient of viscosity, r the radius of the capillary, l its length, V the volume passing through the capillary under a pressure p, in the time t. We see from these two equations that for a given volume of liquid and a given capillary the time of outflow will be inversely proportional to the pressure causing flow. This, in brief, is Poiseuille's law. This equation has been found to hold fairly well for pure liquids within normal ranges of pressure and for small capillaries whose length exceeds a minimum value. In the more accurate work a correction for kinetic energy is introduced. The following equation is given by Bingham and White (1912):

$$\eta = \frac{\pi \text{ g } r^4 \text{ p t}}{8 \text{ V } (l + \lambda)} - \frac{M \rho V}{8 \pi \text{ t } (l + \lambda)}$$

Where η is the coefficient of viscosity, g the gravitational constant, p the pressure, t the time taken for the volume of liquid V to flow through the capillary of length l and radius r. ρ is the density of the liquid, M is a constant to which the author assigns the value of 1.12, and λ is a correction to be made to the length of the capillary on account of viscous resistance outside the capillary.

Reynolds (1883) found that, for large tubes, as soon as the pressure forcing the liquid through the tubes exceeded a certain value, Poiseuille's law no longer held and the movement of the liquid through the tube instead of being smooth became turbulent. Glaser (1907) investigated the effect of the diameter and the length of the capillary on the validity of Poiseuille's law and found that for very viscous substances Poiseuille's law held, while with less viscous substances it did not.

Bose (1911), Bose and Bose (1911), Sorkau (1911), and others also investigated the effect of pressure on flow through capillary tubes. Sorkau (1912) explained the flow of liquids through a capillary in the three states of turbulence as follows: Turbulence No. 1 was the ordinary flow in which Poiseuille's law holds. Turbulence No. 2 was a transition condition between Turbulence Nos. 1 and 3. Turbulence No. 3 was a condition which exists at higher pressures. In this case the liquid moves through the capillary more or less like a solid rod, and between the column of liquid and the wall a portion of the liquid forms a smooth sliding surface.

While there are numerous forms of capillary viscosimeters, perhaps the Ostwald type is the best known. In using this apparatus the time of outflow for a liquid whose viscosity is known must first be determined, then the viscosity of any other liquid may be determined from the equation, knowing the time of outflow and the densities.

$$\frac{\eta}{\eta_1} = \frac{D \text{ } t}{D_1 \text{ } t_1}$$

Where η and η_1 are the viscosities of the standard and unknown liquids respectively, t and t_1 are the times of outflow and D and D_1 are the densities. For very refined work, Bingham and White (1912) suggest a correction for differences in kinetic energy.

A second type of instrument has been devised for the determination of the viscosity of a liquid by a torsional balance. This method appears to have been first used by Coulomb (1800). A disc, ball, or cylinder is suspended by means of a fine wire in a cylinder containing the liquid being investigated. In instruments of the Doolittle (1893a) (1893b) type the inner ball is usually rotated through one revolution and then released. The damping effect of the liquid on its rotation indicates the viscosity, the more the rotation is retarded the higher the viscosity of the liquid. In instruments of the Couette (1890) type the outer cylinder is rotated at a constant speed until the torsional force exerted on the wire by the suspended cylinder balances the viscous resistance of the liquid, and remains in a fixed position. The angular displacement is then read off on some convenient scale. In instruments of this type care is taken to eliminate the effect of the ends, as for example, the apparatus, used by Perry, Graham, and Heath (1893), Drew (1901), Hatschek (1913a) (1913b), and others, which permits the calculation of the viscosity coefficient from the dimensions of the apparatus.

MacMichael (1915) devised an apparatus of this type which has been used more or less in the United States. In this instrument a disc was suspended in a cylinder containing the liquid being investigated. It was necessary to calibrate the instrument with a solution of known viscosity, in order to express the results in absolute units.

Hays and Lewis (1916) devised an apparatus quite similar to the MacMichael viscosimeter.

Herschel (1920), of the Bureau of Standards, in a study of the MacMichael viscosimeter found it impossible to calculate the viscosity of a liquid from the dimensions of the instrument. In an attempt to more nearly approach ideal conditions, a modification of the MacMichael instrument was developed by Eimer and Amend in which a cylinder of 1 centimeter diameter suspended in an outer cylinder of 3 centimeters diameter was substituted for the disc in the old instrument. The lower end of the inner cylinder was concave so that a bubble of air was caught in the recess, thus eliminating the lower end. The outer cylinder was rotated at a constant speed of 19.1 revolutions per minute. These conditions thus simulate very closely the definition of the unit of viscosity in which the planes are 1 centimeter apart and the difference in velocity is 1 centimeter per second.

Viscosity measurements have attained a wide use in the testing of lubricating oils. Technical viscosimeters have been devised for this purpose by Saybolt, Enger, Redwood, Tagliabue, Dudley, Scott, Doolittle, Magruder, and others. These instruments and the methods of use are all described by Gill (1910) as chairman of a committee of the American Society of Testing Materials on standard tests for lubricants.

Equations for the viscosity of colloidal systems.—Einstein (1906) (1911), Hatschek (1910) (1911), Arrhenius (1916), Smoluchowski (1916), and Hess (1920a) have developed equations for the viscosity of colloidal solutions based more or less on theoretical considerations. These equations all express the viscosity of the colloidal systems in terms of the viscosity of the dispersion medium and some relationship with the volume occupied by the dispersed phase.

Bingham and Durham (1911) found that the decrease in fluidity of clay suspensions was directly proportional to the volume concentration of the dispersed phase. Bingham (1916), in a further study on clay suspensions, showed that as the concentration of the clay increased, the system passed from the viscous to the plastic flow. In order to cause the flow of plastic substances, the shearing force must exceed a definite minimal value. This minimal value he calls the friction constant. In his study of plastic flow through capillary tubes, Bingham found that if the friction constant was subtracted from the pressure producing the flow, within certain limits, the volume of flow was then directly proportional to this difference. He thus showed that there were two factors entering into the flow of plastic materials, namely, the friction constant and the mobility. Bingham (1922) has recently published in book form a discussion of fluidity and plasticity.

Special factors which influence the viscosity of colloids.—The viscosity of pure liquids and molecular solutions was found to be independent of the rate of shear within the lower limits. Even at extremely low rates of shear, Duff (1905), Gurney (1908a), and Griffiths and Griffiths (1921) found that Poiseuille's law held. This was not found to be the case with some colloidal solutions, as shown by Hess (1910) (1912a) (1912b) (1920a) (1920b), Hatschek (1913a), Rothmann (1914) and especially Rothlin (1919), the colloidal solution always becoming less viscous at the higher rates of shear.

Rothlin, using the horizontal capillary tube method, found that for a 1 per cent gelatin sol at 15.5° C. the deviations from Poiseuille's law were greater the longer the solution stood after preparation. He also found that the lower the temperature at which the determination was carried out the greater the deviation. Albumin solutions deviated at the lower rates of shear, while the law seemed to hold with casein sols.

Starch sols were prepared by heating both the soluble and insoluble modifications. Poiseuille's law was found to hold with the soluble starch but not with the insoluble starch, neither did it hold with agar-agar or soap solutions. Rothlin concludes that Poiseuille's law does not hold with those sols which have a tendency toward gel formation, and explains that in such sols a cohesive force must be overcome.

Rothmann (1914), in his investigations on the viscosity of blood, found that for frogs' blood Poiseuille's law held for a capillary tube having a diameter of 465μ, but it did not hold for a tube whose diameter was 100μ. He believed that the validity of Poiseuille's law depended on the ratio of particle size to capillary diameter, the larger the value of this ratio the greater the deviation from the law.

Humphrey and Hatschek (1916), using a modified Couette apparatus, found that the viscosity of rigid particles was a function of the rate of shear.

Shorter (1906) (1909) found that saponin, peptone, and albumin solutions affected the viscosity of the surface of their solution, so that a definite change in viscosity could be detected when a complete layer of molecules was formed on the surface. Dienes (1911), using a Coulomb viscosimeter, found the viscosity of water and salt solutions increased with the depth of immersion of the disc; while with sols of egg white, horse blood serum, and methyl violet the greatest viscosity was obtained just beneath the surface, the viscosity at first decreasing with increasing depth of immersion until a minimum value was reached, and then increasing. Gurney (1908b), using a modified Couette apparatus, found that water exhibited considerable rigidity of surface, amounting to four or five times its viscosity at extremely low rates of shear.

Odén (1912), in his investigations on the properties of very concentrated sulphur hydrosols, measured the viscosity of the sols of various concentrations. He found that the sols whose particles were in a finer state of subdivision had the greatest viscosity. The difference was more marked at the higher concentrations.

Schroeder (1903), Ostwald (1905) and others have found that prolonged boiling decreases the viscosity of gelatin solutions. Some of the factors influencing the viscosity of gelatin and glues have recently been investigated by Bogue (1920) (1921).

Woudstra (1908) carried out an investigation of the viscosity of suspensoids. He (1911) found that the coagulation of iron oxide sols could be followed by measuring the viscosity of the solution. A decrease in viscosity occurred which he attributed to a decrease in the degree of dispersion. This decrease was followed by an increase in viscosity due to the large particles coagulating out and stopping up the capillary. Freundlich and Ishizaka (1913) investigated the change in the viscosity of aluminum hydroxide sols with time, after the addition of a coagulating agent. They found that the viscosity did not change very much at first, but later increased rather rapidly. They explain this failure of the sol to show an immediate increase in viscosity as due to time being required for the adsorption of the coagulating agent.

Chick and Martin (1912), Chick and Lubrzynska (1914), and Chick (1914) used the viscosity of protein solutions as a means for the determination of the hydration of proteins in solution. They found by applying Hatschek's (1911) equation that as much as 8.6 cc. of water was taken up by one gram of casein. Arrhenius (1916) took exception to such high hydration values and by applying his own equation obtained much lower figures.

Effect of electrolytes on viscosity of emulsoids.—Laqueur and Sackur (1903) in their study of casein found that the addition of acid and alkali to the casein sols affected their viscosity. They attributed this effect to a change in the ionization of the casein. They found that the viscosity passed through a maximum with increasing hydroxyl-ion concentration. Schroeder (1903) investigated the effect of hydrochloric acid on the viscosity of gelatin. Pauli and Handovsky (1909), and Handovsky (1910) studied the effect of the addition of various amounts of different acids and alkalies on the viscosity of albumin. These authors found that the different acids, when compared on the basis of normality, affected the viscosity in various ways. Sulfuric acid caused only a slight increase, as did acetic acid; trichlor acetic acid caused a slight increase and then a fall; dichlor acetic acid caused a considerable rise and then a fall; while monochlor acetic acid caused a very steep rise over the entire range. Citric acid caused a steady rise over the entire range; oxalic acid caused a rise and then a fall; while hydrochloric acid caused a very great rise and then a very sharp fall in viscosity as the concentration of acid increased.

The effect of alkalies was found to be related more or less to their dissociation constants, the greater the dissociation constants the greater the increase in viscosity produced. There was no decrease in viscosity at the higher concentrations. Their investigation was limited mainly to the monovalent bases. The highest concentrations investigated in the case of both acids and bases was 0.05 normal.

Michaelis and Mostynski (1910) studied the effect of acid and alkali on serum from which the globulin had been separated by prolonged dialysis. They found that the addition of acid at first caused a decrease in viscosity in the region of a hydrogen-ion concentration of $0.28-2.0 \times 10^{-5}$, and then an increase with increasing acidity. This decrease was not mentioned by Pauli and Handovsky (1909). The addition of alkali to completely dialyzed serum always caused an increase in viscosity.

Pauli (1913) found that on the addition of hydrochloric acid to albumin the maximum viscosity was reached at the point where the value for the difference between bound hydrogen and bound chloride ions was the greatest. He also pointed out that by the addition of increasing amounts of hydrochloric acid to gelatin, the osmotic pressure at first increased to a maximum and then decreased. Expressing the results graphically, the curve for osmotic pressure was very similar in form to the viscosity curve produced under the same conditions.

In recent years numerous investigators have studied the effect of electrolytes on the viscosity of protein sols. Noteworthy among these is Loeb (1920a) (1920b) (1920c) (1921a), who presented evidence tending to show that the maximum viscosity with the various acids was reached at the same hydrogen-ion concentration, and that for a given protein the same high point was reached with the various acids, with the exception of sulfuric acid, which always produced a smaller increase in viscosity than the other acids. The same results in general were found to hold true with the alkalies. The monovalent bases reached the same maximum at the same hydroxyl-ion concentration. The divalent bases differed in that they did not cause such a great increase in viscosity. Loeb explained the behavior of salts in decreasing the effect of acids on viscosity as due to the anion alone, while the cation was thought to be the effective ion in the case of the alkalies. Loeb (1921b) (1921c) (1921d) (1921e) (1921f) agrees with the explanation of imbibition as put forward by Proctor (1914), Proctor and Wilson (1916), and Wilson and Wilson (1918), based on the Donnan (1911) equilibrium as established by Donnan and Harris (1911), Donnan and Allmand (1914), and Donnan and Garner (1919).

Zoller (1919) (1920) (1921) studied the effect of different hydrogen-ion concentrations on the viscosity of casein solutions and found the maximum viscosity occurred at a pH of 9.

Ostwald (1913) points out that while the viscosity of a molecular solution is defined by the concentration and the temperature, another factor enters into the definition of the viscosity of a suspension, namely, the degree of dispersion. In the case of emulsoids, Ostwald (1913) gives ten factors which may influence viscosity, namely, (1) concentration, (2) temperature, (3) degree of dispersion, (4) solvate formation, (5) electric charge or ionization, (6) previous thermal treatment, (7) previous mechanical treatment, (8) inoculation with small quantities of more viscous colloids, (9) time, and (10) addition of both electrolytes and non-electrolytes. Another factor which is of extreme importance should be added to this list, namely, the rate of shear.

Practical applications of the viscosity of colloids.—The viscosity of colloidal solutions of rubber, soluble cellulose compounds, starch, soap, paints, clays, glues, gelatin, etc., has been investigated by numerous workers. With certain limitations it has been found that the viscosity determination could be made to serve as an index to quality.

In biology and medicine certain changes in the animal organism have been found to manifest themselves by changes in the viscosity of the body fluids such as the blood, milk, etc.

EXPERIMENTAL

THE PROBLEM

The object of this work was to continue the investigations of flour strength along the lines of colloid chemistry, (1) by studying the use of viscosity measurements as a means of determining the imbibitional power of the gluten proteins without their removal from the flour; (2) to see what correlation, if any, could be derived between the viscosity measurements and the baking strength of the flour.

In the work reported here no attempt was made to investigate all the factors which might influence the viscosity of flour-in-water suspensions but rather to keep as many factors constant as possible while comparing the behavior of the various flours subjected as nearly as possible to the same conditions. The measurements reported here are more truly a measure of the imbibitional capacity of the flour constituents in a state of coarse suspension as shown by the resistance of their suspensions to a shearing force. In this work no attempt has been made to distinguish between viscosity and plasticity or to determine the plasticity constants for those mixtures which were undoubtedly plastic. The term "viscosity" has been used in a rather loose sense throughout to indicate all resistance offered by the suspensions to the shearing force applied.

FLOURS USED

For the first phase of the work, that is, the effect of various acids on the imbibitional power of the flour as measured by viscosity, two flours were used; B-780, a strong flour milled from northern spring wheat, an especially strong patent flour prepared for a select trade; and B-783, a patent flour milled from soft club wheat grown at Genessee, Idaho. These two flours contained practically the same percentage of crude protein. B-780 had a total protein content

(N×5.70) of 12.13 per cent; the water-soluble protein, determined by digesting for 40 minutes at 10° C., was 1.63 per cent; and the loaf volume, using 300 grams of flour, was 1639 cc. Flour B-783 contained 12.15 per cent of total protein and 1.67 per cent of water-soluble protein, and gave a loaf volume of 1530 cc. Additional analytical and baking data may be found in the paper by Sharp and Gortner (1922). At the beginning of this investigation a considerable quantity of these two flours was placed in air-tight containers and stored in a cold storage plant at a temperature of approximately 3° C.

The second group of flours investigated was kindly supplied by Walter Marshall, of the United States Bureau of Markets. The baking and analytical data were also furnished by him.

The third group of flours was a series collected by the American Institute of Baking from various parts of North America and subjected to a joint investigation by L. A. Rumsey, F. A. Collatz, and Paul F. Sharp, in an effort to investigate as many factors as possible which might be related to flour strength. Rumsey (1922) and Collatz (1922) presented separate reports upon their phases of the investigation.

METHODS AND GENERAL OBSERVATIONS

In beginning the experimental work on the viscosity of flour-in-water suspensions, the method employed by Lüers and Ostwald (1919) was used. A viscosimeter of the Ostwald type was constructed which had a bulb of about 23 cc. capacity. A bulb of this size was chosen in order that 25 cc. of liquid might be used to operate the viscosimeter. The capillary had a length of about 9 centimeters and a diameter of 0.85 millimeters. The time of outflow for water as determined by a stop watch was 91.5 seconds. The viscosity determinations were all carried out in a glass-walled thermostat at a temperature of 25° C.

As Lüers and Ostwald (1919) used a 20 per cent flour-in-water suspension for their investigations of the effect of lactic acid on the viscosity of wheat flours, this same concentration was chosen for the first part of the investigation.

In the first place it was noticed that successive readings on the same 20 per cent flour-water mixture without the addition of acid gradually decreased. This behavior was observed more or less with all the flours investigated. As an example of this behavior some of the data obtained with flour No. 2116, milled from No. 3 dark northern spring wheat and producing a loaf of large volume, are given. The determinations were made one after the other as fast as possible. After each reading, air was blown through the mixture in the viscosimeter to stir it thoroly, and the next reading was taken immediately afterward. It was at first thought that this decrease in viscosity might be due to the effect of carbon dioxide of the air, so in several instances the air used in stirring the mixture was first passed through a solution of sodium hydroxide. However, this procedure did not in the least affect the results.

One set of results obtained with this flour, expressing the rate of outflow in fifths of seconds, the first reading being taken 15 minutes after preparation of the flour-in-water, is as follows: 329, 324, 329, 314, 304, 302, 303, 289, 283, 283, 281, 281, 270, 262, 260, 250, 252, 242, 242, 236, 236, 236, 230, 229, 225, 213, 219, 213, 214, 217, 212. From other observations it was believed that this effect was not due to time of standing. This point was investigated by preparing mixtures of flour and water, determining their viscosity, and then letting them stand for an hour or more. Results obtained with the same flour are presented as an example of the effect of standing. The time of outflow observed 15 minutes after the preparation of the mixture was 341 and a reading immediately afterwards gave 346. The material was then allowed to stand for an hour in the viscosimeter. It was then mixed by blowing air through the apparatus and the reading obtained was 346 and the subsequent reading was 341.

It was thus very difficult to decide which reading was the correct one. It was thought that perhaps the difficulty might be due to the method of preparation of the suspension, therefore three different methods were tried: (1) the weighed amount of flour was mixed with the required amount of water by suddenly shaking; (2) the weighed amount of flour was placed in a beaker and water was added slowly from a burette, the flour being stirred in the meantime with a stirring rod; (3) enough water was first added to the weighed amount of flour in a mortar to make a dough, and this dough was kneaded with the pestle for about three minutes and then the rest of the water was gradually worked in with the dough, forming the suspension.

The results obtained with the three methods seem to indicate that the third method gives the most concordant results with the original suspension before acid was added. Serious difficulties were encountered by the use of Methods 2 and 3 when adding the acid to mixtures obtained in this way, for after the addition of a given amount of acid the viscosity gradually increased until after a time a maximum was reached and from then on the viscosity declined. In one instance it was only after the twenty-ninth reading that the maximum viscosity was reached, the readings increasing from 462 fifths of seconds to 1003 fifths of seconds. In the first method this behavior was not so marked, the maximum being reached after the second and third readings. This was believed to be due to the fact that in the first method the gluten particles were mechanically separated to a greater extent, thus presenting a greater surface upon which the acid might act; while in the other cases, in spite of the care taken to prevent it, small particles of gluten were present and time was required for the acid to diffuse to their center, thus causing maximum swelling.

Another difficulty encountered was the effect of air bubbles producd by the shaking, in the first method, or by the air that was blown through the apparatus to stir the mixture. In an attempt to prevent the formation of air bubbles it was necessary in many cases to remove the viscosimeter from the bath and invert it carefully several times in order to accomplish the mixing.

The difficulties encountered indicated that a definite mechanical procedure must be adopted if interpretable results were to be obtained, also that the time factor must be kept constant. The greatest objection to the Ostwald type of viscosimeter was found in attempting to keep the time factor constant. In the investigation of the effect of additions of various amounts of normal lactic acid to the 20 per cent flour-in-water suspensions, the time of outflow for the flours investigated was found to range from 41 seconds to more than 8 minutes. The attempt was made to run at least four determinations for each addition of acid. The effect of various concentrations of lactic acid on twelve different flours was investigated, but the results were so erratic that it was thought not worth while to present the data here, and the use of the Ostwald viscosimeter was accordingly abandoned.

It was thought that perhaps a viscosimeter of the torsion balance type might eliminate some of the difficulties encountered with the Ostwald viscosimeter. A MacMichael (1915) viscosimeter of the old type was used. It was soon realized that comparative results were all that could be obtained without the unnecessary expenditure of a great amount of time. The experiments were all carried out at 25° C. The determinations were performed in a constant temperature room. The flour and water were always allowed to come to the temperature of the room before the suspensions were made. In this first set of determinations, enough flour was taken to make 25 grams on the moisture-free basis. To this weight of flour enough water was added to make a total of 100 grams of water. The actual amount of water added was thus approximately 96.5 grams. This mixture of flour and water was allowed to stand one hour with occasional shaking. This interval of time was chosen because Bailey and Collatz (1921) had found that the quantity of electrolytes extracted from flour by water at first increased rapidly with time of extraction but that later the amount extracted became nearly constant. It was therefore believed that an easily duplicable level of electrolyte content could be obtained at the end of one hour and that the proteolytic action of enzymes on the gluten would be inappreciable during this short period. A departure from the general method for using viscosimeters of this type was adopted because comparative results are all that were expected, and the attempt was made to make the method as rapid as possible. Instead of waiting for the reading on the dial to become constant, the motor in the instrument was started and the first high rotation of the dial was read. The motor was then stopped, the material in the cup was stirred several times with the plunger while the cup was rotated with the hand, and another reading was immediately taken. This procedure permitted duplicate readings to be taken very rapidly and did not introduce appreciable errors due to settling out of the suspension. The duplicate readings obtained by this method always checked as close as the dial could be read accurately. The results of the determinations carried out by this method are all reported in terms of angular rotation in degrees MacMichael, a reading of 300 degrees MacMichael indicating that the dial has made one complete revolution. The wires were tested frequently to see if the limit of their elasticity had been exceeded. The readings were not converted over to absolute viscosity units because doubts were entertained as to the true value of the results expressed in absolute units.

The results would seem to indicate that the viscosity in some of the flour suspensions, at least, varied with the rate of shear and that even the different flours vary in this respect. Most of the shear probably came between the bottom of the disc and the cup where the rate of shear increased from zero at the point of common axis to probably its maximum value near the outer under edge of the disc, thus the material was not all subjected to the same rate of shear.

In order to have some idea as to the absolute viscosity values, the instrument was always standardized against sucrose solutions. Owing to its inertia the liquid did not attain its maximum speed at the time the reading was taken, and as a volume of 100 cc. was used in each case, any difference in density between two liquids would affect the viscosity readings. In this first series of experiments the wire was standardized against a sucrose solution whose specific gravity compared with water at 25° C. was 1.185 and whose absolute viscosity standardized by means of water in an Ostwald viscosimeter was found to be 5.73 centipoise. The speed of the motor was so adjusted that the reading obtained with this sucrose solution was as nearly as possible 14.3 degrees, MacMichael. The specific gravity of the flour-in-water suspension compared with water at 25° C. was determined in two instances and was found to be approximately 1.086.

VISCOSITY OF THE ORIGINAL FLOUR-IN-WATER SUSPENSION AS AFFECTED BY VARIOUS AMOUNTS OF DIFFERENT ACIDS

The strength of the various normal acid solutions was determined by titrating aliquots with 0.10 normal sodium hydroxide, using phenolphthalein as an indicator.

In this first series of experiments the effect of the addition of different amounts of normal solutions of various acids on the viscosity of flours B-780 and B-783 was studied. For each determination 100 cc. of the suspension prepared as previously described was placed in the cup of the viscosimeter and four separate readings were made. A definite amount of a normal solution of the acid being investigated was then added. A 1-cc. burette graduated to 0.01 cc. was used to measure the acid. After each addition of acid the mixture was stirred and four separate readings were taken. The additions of acid were continued until a total of 10 cc. had been added.

The effect on viscosity of this dilution with 10 cc. was studied by taking mixtures of various readings ranging from 17 to 230 and adding 10 cc. of water. In all, forty such determinations were made and the average taken. The dilution was found to cause a decrease in the viscosity of 22.9 per cent, the maximum deviation from this average was found to be 1.9 per cent. The effect of dilution was the same with the two flours within experimental error. The assumption was made that the effect of dilution on the viscosity was linear and the results given in the tables have been corrected for dilution on that basis.

The effect on the viscosity of the addition of the following total amounts of normal acid was determined: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1, 1.20, 1.50, 2, 2.50, 3, 4, 5, 6, 8, and 10 cc. With flour B-783 there was practically no change in viscosity until a total of 1 cc. of acid had been added, while with flour B-780 the increase began with the addition of a lesser amount. It was thought not worth while to record all the results obtained with the smaller additions of acid, so these were omitted in Table III, but in order to show the onset of the increase in viscosity the effect produced by the addition of the smaller amounts of a few of the acids is given in Table II.

TABLE II

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Acid Solutions

Twenty-five grams of flour on the dry basis was treated with enough distilled water to make 100 cubic centimeters of water and digested with occasional shaking at 25° C. for one hour. One hundred cubic centimeters of this mixture was taken for the viscosity measurements. All determinations were carried out at the temperature of 25° C., and were corrected for dilution back to the original volume of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. acid added	Hydrochloric acid		Lactic acid		Acetic acid	
	B-780	B-783	B-780	B-783	B-780	B-783
0.00	63	39	64	36	63	37
0.10	66	41	65	37	62	37
0.20	68	42	67	38	63	37
0.30	69	42	71	38	63	37
0.40	76	41	82	38	64	37
0.50	88	40	94	38	69	37
0.60	99	40	110	39	72	37
0.70	120	41	124	41	78	36
0.80	142	43	143	44	82	36
0.90	165	48	157	47	88	36
1.00	187	54	172	52	91	36

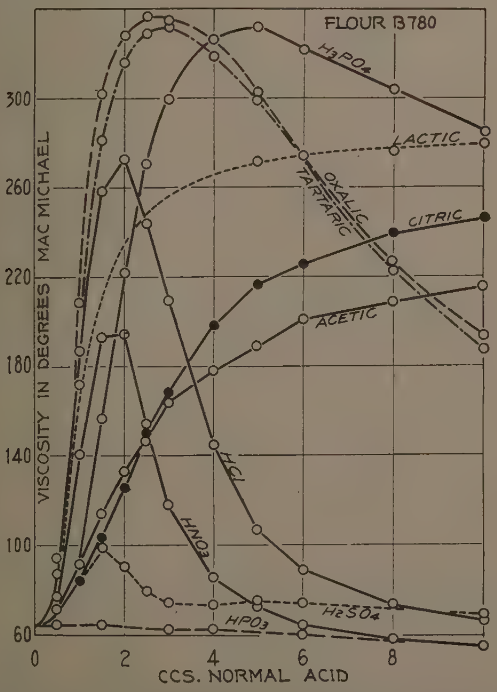

Fig. 1. Viscosity of 100 cc. of 20% Flour-in-Water Suspensions of Strong Flour B-780 as Affected by Different Amounts of Various Acids (Compare with Fig. 2.)

In Table III and Figures 1 and 2 the results obtained with the larger amounts of acid are given. All the values reported in the following tables are the average of the determinations carried out on at least two separate flour suspensions. In order to show the accuracy of these duplicate determinations a few samples have been grouped together and are given in Table IV.

TABLE III

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Acid Solutions, with pH of the Resulting Mixture

Twenty-five grams of flour on the dry basis was taken in each instance, treated with 100 cubic centimeters of distilled water, and digested with occasional shaking at 25° C. for one hour. One hundred cubic centimeters of this mixture was taken for the viscosity measurement. All determinations were carried out at the temperature of 25° C., and were corrected for dilution back to the original volume of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. acid added	Hydrochloric acid				Lactic acid			
	B-780		B-783		B-780		B-783	
	Visc	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	63	5.84	39	5.87	64	5.84	36	5.87
0.50	88	4.75	40	4.95	94	4.84	38	4.90
1.00	187	3.92	54	4.25	172	4.14	52	4.41
1.50	258	3.32	104	3.64	215	3.91	82	4.07
2.00	273	2.65	128	3.12	235	3.75	105	3.88
2.50	244	2.27	115	2.57	248	3.55	119	3.74
3.00	209	1.96	93	2.31	255	3.46	125	3.65
4.00	145	1.79	56	1.89	265	3.32	132	3.49
5.00	107	1.60	41	1.69	272	3.23	136	3.39
6.00	89	1.39	34	1.55	272	...	136	3.28
8.00	73	1.23	29	1.37	277	3.02	139	3.14
10.00	66	1.17	25	1.22	280	2.95	140	3.04

cc. of N. acid added	Tartaric acid				Oxalic acid			
	B-780		B-783		B-780		B-783	
	Visc	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	66	5.86	36	5.90	65	5.83	36	5.82
0.50	83	4.67	37	5.07	87	4.67	36	4.99
1.00	179	4.11	40	4.41	208	4.15	35	4.32
1.50	281	3.67	56	3.97	302	3.71	48	3.90
2.00	317	3.36	84	3.67	328	3.43	71	3.58
2.50	330	3.12	104	3.42	337	3.11	95	3.35
3.00	332	2.83	113	3.21	335	2.94	108	3.09
4.00	320	2.52	118	2.86	326	2.53	113	2.73
5.00	301	2.26	106	2.50	302	2.28	105	2.42
6.00	272	2.06	94	2.25	274	2.12	93	2.15
8.00	223	1.87	72	2.01	227	1.91	72	1.92
10.00	188	1.72	54	1.84	194	1.78	54	1.78

TABLE III—*Continued*

cc. of N. acid added	Sulfuric acid				Acetic acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	66	5.91	38	5.85	63	5.95	37	5.83
0.50	67	4.76	38	...	69	5.08	37	5.16
1.00	86	4.02	33	...	91	4.71	36	4.82
1.50	98	3.41	33	3.62	114	4.55	41	4.60
2.00	90	2.86	33	...	133	4.43	46	4.46
2.50	79	2.42	33	...	147	4.29	50	4.40
3.00	74	2.19	33	2.40	163	4.23	54	4.31
4.00	73	1.91	31	...	178	4.11	63	4.18
5.00	74	1.75	31	...	189	4.01	74	4.07
6.00	74	1.62	30	...	201	...	83	4.01
8.00	72	1.45	28	...	209	3.83	92	3.88
10.00	69	1.36	27	1.39	216	3.76	105	3.79

cc. of N. acid added	Citric acid				Ortho-phosphoric acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	65	5.96	37	5.82	66	5.90	37	5.85
0.50	68	4.97	36	5.16	69	5.24	39	5.43
1.00	83	4.60	36	4.72	94	4.73	38	4.97
1.50	103	4.29	35	4.46	156	4.25	48	4.62
2.00	126	4.07	38	4.25	222	3.86	72	4.28
2.50	150	3.88	43	4.07	270	3.62	110	3.98
3.00	168	3.76	50	3.93	299	3.32	138	3.65
4.00	199	3.55	68	3.60	326	2.95	157	3.25
5.00	217	3.37	81	3.49	332	2.66	163	2.91
6.00	226	3.26	91	3.35	322	2.47	155	2.47
8.00	240	3.09	99	3.18	304	2.26	146	2.38
10.00	247	2.95	103	3.03	285	2.14	136	2.22

cc. of N. acid added	Nitric acid				Meta-phosphoric acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	64	5.96	35	5.85	63	5.90	34	5.85
0.50	77	4.85	34	5.06	63	...	33	...
1.00	140	3.99	39	4.48	62	...	32	...
1.50	193	3.33	57	3.60	62	...	...	...
2.00	195	2.82	66	3.08	61	...	31	...
2.50	154	2.35	55	2.63	...	...	...	...
3.00	118	2.15	43	2.27	62	...	...	...
4.00	85	1.87	33	1.79	62	...	...	...
5.00	73	...	28	1.69	...	...	27	...
6.00	64	1.54	27	...	60	...	...	...
8.00	58	1.36	26	1.35	...	...	...	...
10.00	55	1.23	23	1.23	55	2.26	26	2.33

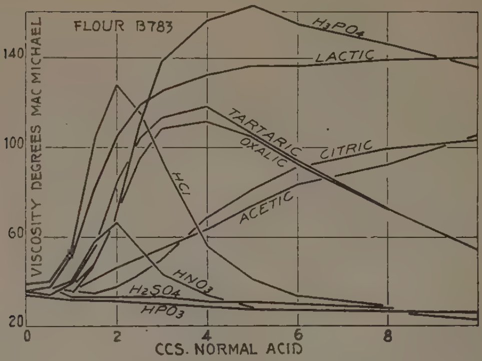

Fig. 2. Viscosity of 100 cc. of 20% Flour-in-Water Suspensions of Weak Flour B-783 as Affected by Different Amounts of Various Acids (Compare with Fig. 1.)

TABLE IV

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Lactic and Acetic Acid Solutions Showing Agreement of Duplicate (A and B) Determinations

Twenty-five grams of flour on the dry basis was taken in each instance, treated with enough water to make 100 cubic centimeters and digested with occasional shaking at 25° C. for one hour. One hundred cubic centimeters of this mixture was taken for the viscosity measurements. All determinations were carried out at the temperature of 25° C. and are corrected for dilution back to the original volume of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. acid added	Lactic acid				Acetic acid			
	B-780		B-783		B-780		B-783	
	Visc.	Visc.	Visc.	Visc.	Visc.	Visc.	Visc.	Visc.
	A	B	A	B	A	B	A	B
0.00	64	64	36	37	65	61	37	37
0.50	94	94	39	38	70	68	37	37
1.00	174	170	50	53	91	90	35	36
1.50	218	212	80	84	116	112	41	41
2.00	237	233	105	105	135	131	46	46
2.50	250	246	119	119	147	147	50	50
3.00	254	255	125	124	166	160	54	54
4.00	264	265	135	129	179	177	64	62
5.00	272	272	139	133	190	188	73	74
6.00	272	271	139	133	202	199	82	83
8.00	276	277	143	135	209	209	92	91
10.00	280	280	144	136	215	217	107	103

In Table V are given the results obtained with phosphoric, monochlor acetic, and dichlor acetic acids. In this case a new adjustment of the wire in the viscosimeter was made. For standardization a 60 per cent sucrose solution of a density at 25° C. of 1.284 and whose absolute viscosity was 43.86 centipoise was used [Bingham and Jackson (1917)], the speed of the motor and the distance of the plunger from the bottom of the cup were so adjusted as to make the reading as nearly as possible 87.7 degrees MacMichael. It was feared that the results obtained with this readjusted wire would not be the same as those obtained with it in the previous condition. The effect of lactic acid on the viscosity of the two flours was therefore redetermined in order to give a basis for comparison with the preceding series. It will be noted that the first reading taken with flour B-783 is practically the same in both series, but with B-780 the original reading is much higher in the second series than in the first. This difference between the two flours holds more or less when the effects of the different additions of lactic acid are compared.

TABLE V

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Acid Solutions, with the pH of Resulting Mixture

Twenty-five grams of flour on the dry basis was taken in each instance, treated with 100 cubic centimeters of distilled water and digested with occasional shaking at 25° C. for one hour. One hundred cubic centimeters of this mixture was taken for the viscosity measurements. All determinations were carried out at the temperature of 25° C., and are corrected for dilution back to the original volume of 100 cubic centimeters. The wire in this case was standardized with a 60 per cent sucrose solution whose absolute viscosity is 43.86 centipoise. This solution gave a reading of 87.7 degrees MacMichael.

cc. of N. acid added	Lactic acid				Phosphoric acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	79	5.84	35	5.87	80	5.85	35	5.83
0.50	127	4.84	40	4.90	90	5.16	38	5.07
1.00	216	4.14	70	4.41	118	4.60	40	4.85
1.50	259	3.91	102	4.07	180	4.09	47	4.36
2.00	280	3.75	122	3.88	246	3.75	64	4.14
2.50	293	3.55	131	3.74	290	3.18	94	3.82
3.00	297	3.46	138	3.65	315	3.03	123	3.62
4.00	299	3.32	143	3.49	332	2.82	156	3.13
5.00	302	3.23	144	3.39	329	2.47	160	2.76
6.00	301	...	143	3.28	314	2.13	156	2.49
8.00	306	3.02	146	3.14	285	2.07	146	2.18
10.00	308	2.95	147	3.04	257	1.96	129	1.94

cc. of N. acid added	Monochlor acetic acid				Trichlor acetic acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	79	5.85	35	5.80	81	...	33	...
0.50	110	4.70	39	4.82	89	...	33	...
1.00	206	3.94	52	4.13	120	...	36	...
1.50	275	3.58	89	3.74	147	...	39	...
2.00	303	3.26	120	3.38	135	...	41	...
2.50	311	3.04	128	3.21	115	...	37	...
3.00	311	2.91	129	3.03	104	...	35	...
4.00	295	2.74	130	2.81	96	...	31	...
5.00	284	2.59	126	2.69	91	...	31	...
6.00	271	2.49	118	2.57	84	...	31	...
8.00	254	2.35	115	2.42	82	...	31	...
10.00	240	2.23	106	2.32	77	...	29	...

EFFECT OF ADDITION OF VARIOUS AMOUNTS OF NORMAL SOLUTIONS OF VARIOUS ACIDS ON HYDROGEN-ION CONCENTRATION

The hydrogen-ion concentration was determined only when there was an appreciable change in the viscosity of the mixture. For each determination of hydrogen-ion concentration, 20 cc. of the 20 per cent flour-water mixture was placed in a test tube and a proportional amount of normal acid was added to correspond to the additions as shown in Tables III and V. The test tube was shaken at intervals during half an hour and then the hydrogen-ion concentration was measured. A Leeds and Northrup potentiometer was used for the measurement of the voltage. A type R high sensitivity galvanometer was used as a current detector, and the hydrogen electrodes were of the Bailey (1920) type, so modified as to contain a larger volume of liquid. All determinations were made in a constant temperature room kept at 25° C. A normal KCl calomel electrode and a flowing junction of saturated KCl were used. The millivolt readings were changed to pH by means of the table of Schmidt and Hoagland (1919). The viscosity readings as in Table III as ordinates and the pH values as abscissa are expressed graphically in Figures 3 and 4.

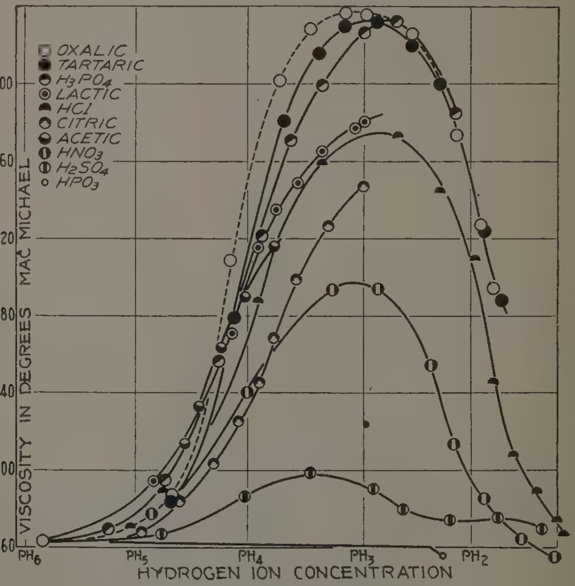

Fig. 3. Viscosity of 100 cc. of 20% Flour-in-Water Suspensions of Strong Flour B-780 at Different Hydrogen-ion Concentrations Produced by Various Acids (Compare with Figs. 1 and 4.)

An attempt was made to measure the hydrogen-ion concentration in the case of the additions of trichlor acetic acid, but constant readings could not be obtained, especially of the higher additions of acid. It was suspected that the trichlor acetic acid was being reduced on the platinum electrode and that hydrochloric acid was being liberated. In order partially to test this hypothesis, a bubbling electrode of the Hildebrand (1913) type was placed in a 0.10 normal solution of trichlor acetic acid and hydrogen was permitted to bubble around the electrode for several hours. At the end of this time the liquid gave a heavy precipitate with silver nitrate. The original solution gave no precipitate. It was later found that dichlor acetic acid behaved in a somewhat similar way, altho not to such a marked extent. No trouble was encountered in the use of monochlor acetic acid with the hydrogen electrode. This would seem to indicate that the first chlorine atom is split off rather rapidly from trichlor acetic acid, the second less rapidly, and the third not at all or only at a very slow rate.

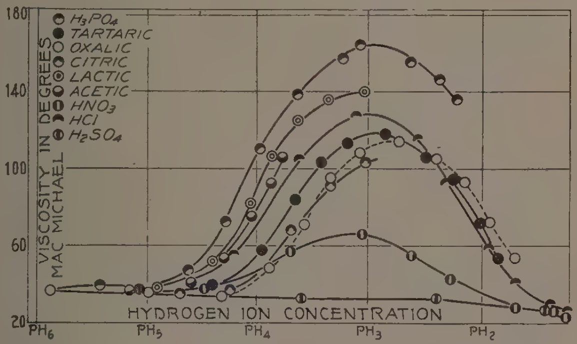

Fig. 4. Viscosity of 100 cc. of 20% Flour-in-Water Suspensions of Weak Flour B-783 at Different Hydrogen-ion Concentrations Produced by Various Acids (Compare with Figs. 2 and 3.)

EFFECT OF ADDED SALTS ON IMBIBITION PRODUCED BY LACTIC ACID

The water with which the flour was digested was made 0.01 normal with respect to various salts with the exception of dibasic potassium phosphate, of which a solution of 0.005 molar was used. The effect of these salts on imbition produced by lactic acid was measured.

In preparing the suspension, 25 grams of flour on the dry basis was treated with enough water and various salts to make 100 cc. of 0.01 normal or 0.005 molar salt solution. The mixture was digested for one hour with occasional shaking. The data obtained on the addition of various amounts of lactic acid to the flour suspension, using flour B-780, are given in Table VI. The results obtained with flour B-783 are found in Table VII. The data of Tables VI and VII are shown graphically in Figure 5.

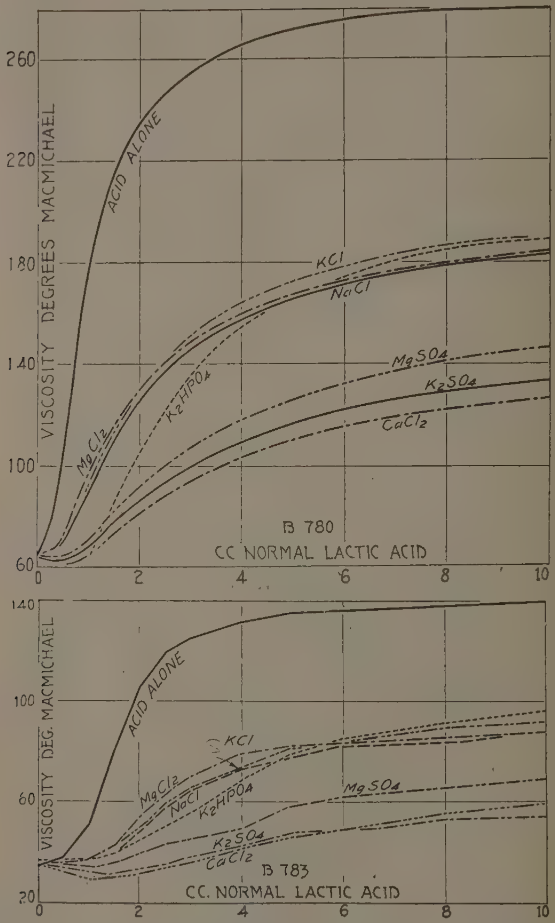

Fig. 5. Viscosity of 100 cc. of 20% Flour-in-Water Suspensions of B-780 and B-783 Made 0.01 Normal with Respect to Various Salts and with the Subsequent Addition of Various Amounts of Lactic Acid

TABLE VI

Viscosity, in Degrees MacMichael, of Flour B-780 as Influenced by Various Amounts of Normal Lactic Acid in the Presence of 0.01 Normal Solutions of Various Salts

Twenty-five grams of flour on the dry basis was taken in each instance and treated with enough salt and water to make 100 cubic centimeters of 0.01 normal salt solution. After one hour digestion with occasional shaking, 100 cubic centimeters of this mixture was taken for viscosity measurements. All determinations were made at 25° C., and are corrected for dilution back to the original value of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. acid added	Lactic acid alone	0.005 M. K_2HPO_4	0.01 N. $MgCl_2$	0.01 N. $MgSO_4$	0.01 N. K_2SO_4	0.01 N. KCl	0.01 N. NaCl	0.01 N. $CaCl_2$
0.00	64	64	63	64	65	65	63	63
0.50	94	61	68	64	62	70	69	61
1.00	172	62	95	70	68	90	89	63
1.50	215	85	115	83	76	114	111	73
2.00	235	107	128	91	87	128	125	82
2.50	248	123	140	101	96	142	137	88
3.00	255	136	147	108	98	151	145	93
4.00	265	155	160	117	109	164	158	103
5.00	272	166	167	126	114	170	166	109
6.00	272	174	173	132	123	176	172	115
8.00	277	185	180	141	129	187	179	121
10.00	280	189	183	146	134	188	183	127

TABLE VII

Viscosity, in Degrees MacMichael, of Flour B-783 as Influenced by Various Amounts of Normal Lactic Acid in the Presence of 0.01 Normal Solutions of Various Salts

Twenty-five grams of flour on the dry basis was taken in each instance and treated with enough salt and water to make 100 cubic centimeters of 0.01 normal salt solution. After one hour digestion with occasional shaking, 100 cubic centimeters of this mixture was taken for viscosity measurements. All determinations were made at 25° C. and are corrected for dilution back to the original value of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. acid added	Lactic acid alone	0.005 M. K_2HPO_4	0.01 N. $MgCl_2$	0.01 N. $MgSO_4$	0.01 N. K_2SO_4	0.01 N. KCl	0.01 N. NaCl	0.01 N. $CaCl_2$
0.00	36	37	36	37	37	37	36	35
0.50	38	38	35	36	35	36	35	33
1.00	52	36	37	33	32	35	35	30
1.50	82	40	43	35	31	42	40	30
2.00	105	45	54	40	33	49	49	32
2.50	119	51	63	43	36	58	58	35
3.00	125	56	70	46	39	66	64	36
4.00	132	69	79	50	43	74	72	43
5.00	136	79	82	59	47	81	78	46
6.00	136	85	83	63	49	85	82	49
8.00	139	93	85	66	56	90	83	53
10.00	140	97	87	69	60	92	87	55

EFFECT OF ELECTROLYTES PRESENT IN THE ORIGINAL FLOUR ON VISCOSITY

It is a matter of common knowledge that the addition of various salts to an acid solution decreases the power of the acid to produce imbibition in emulsoid colloids. That the gluten of wheat is no exception to this rule has been shown by Wood (1907b), Wood and Hardy (1908), Upson and Calvin (1916), Gortner and Doherty (1918), and Sharp and Gortner (1922). The presence of a relatively large amount of soluble electrolytes in the water extract of wheat flour was shown by Bailey and Collatz (1921), who, in addition, found that the quantity of electrolytes bore a definite relation to the ash content of the flour. It was believed that the presence of these salts was exerting an inhibiting effect on the power of the acid to produce imbibition in the flour suspensions studied. In order to ascertain whether or not the marked imbibitional power of flour B-780 with the various acids as compared with flour B-783 was due to the difference in ash content and consequently in soluble electrolytes, 25 grams of flour was treated with one liter of water and after standing for one hour with occasional shaking the material was centrifuged, the liquid containing the soluble ash was decanted, and the residue was made up to a total volume of 100 cc. with distilled water. The effect of lactic acid on the viscosity of the mixture was determined. It was noted that imbibition began with the addition of the first 0.10 cc. of normal acid and that the maximum imbibition reached was much higher than when the electrolytes were not first extracted. This indicated clearly that a considerable proportion of the soluble electrolytes had been removed and that the presence of the electrolytes in the experiments reported in Tables II, III, IV, and V was repressing to a considerable extent the power of imbibition of the proteins present. The true imbibitional powers of the proteins were thus masked to a greater or less extent by the effect of the salts present in the water extract. Even with the electrolytes partially removed by this method, flour B-780 still shows a much greater power of imbibition than does flour B-783, altho the differences were not so marked as in the original untreated flour-water mixture. In the experiments in which the water extract has been removed, the viscosities are more nearly in accord with the loaf volume of the flours than in the previous instance. In the study of the effect of the various acids with the water extract removed, the quantity of flour taken was decreased so that the high viscosity readings obtained would not exceed the limits of elasticity of the wire of the viscosimeter.

In order to ascertain whether or not this treatment removed all the electrolytes which were inhibiting imbibition, an investigation was carried out on two flours selected because of their widely different ash content. Flour 1004 had an ash content of 0.92 per cent on the dry basis and flour No. 1008 had an ash content of 0.52 per cent, thus the ash contents of the two flours were in a ratio of 1 to 1.77.

Experiments were carried out in which 18 grams of flour on the dry basis was treated with enough water to make a total volume of 100 cc. and the mixture was digested with frequent shaking for one hour. At the end of this time the material was centrifuged, the supernatant liquid decanted, and its electrical conductivity measured at 30° C.

A second 18 grams of flour on the dry basis was treated with one liter of distilled water and digested for one hour with occasional shaking. At the end of this time the material was centrifuged and the supernatant liquid discarded. The residue was treated with enough distilled water to make a total volume of 100 cc. and shaken at intervals during 15 minutes, again centrifuged, and the conductivity of the supernatant liquid determined. This procedure was repeated with the exception that after making up to the final volume of 100 cc. the effect of the additions of various amounts of normal lactic acid on the viscosity was determined.

A third set of experiments was performed in which 18 grams of flour on the dry basis was treated with one liter of distilled water and digested with occasional shaking for one hour. The supernatant liquid was removed and the residue again made up to the volume of one liter and digested for half an hour with occasional shaking. The supernatant liquid was then removed and the residue made up to a total volume of 100 cc. and allowed to stand with occasional shaking for 15 minutes. The material was centrifuged and the conductivity of the extract measured. This procedure was repeated except that after making up to the final volume of 100 cc. the effect of the addition of various amounts of normal lactic acid on the viscosity of the mixture was determined. The results of this study are given in Table VIII.

TABLE VIII

Extent to Which Soluble Electrolytes Are Removed from Flour by Extraction with Various Amounts of Water, Together with Effect of Such Removal on Maximum Increase in Viscosity Produced by the Addition of Various Amounts of Normal Lactic Acid

Flour No.	Ash, per cent*	Specific conductance at 30°C. of residue made up to 100 cc.			Highest viscosity reached with lactic acid at 25°C.		
		Direct extraction with 100 cc. of water	After 1 extraction with 1 liter of water	After 2 extractions with 1 liter of water	Without previous extraction	After 1 extraction with 1 liter of water	After 2 extractions with 1 liter of water
1004	0.92	0.00172	0.000110	0.000034	75	329	324
1008	0.52	0.00109	0.000071	0.000028	393	502	498

* Ash calculated on dry basis.

An examination of the results shown in Table VIII indicates that in both cases the extraction with the first liter of water decreased the electrolyte content as indicated by the conductivity determinations to less than one-fifteenth of its original value. The extraction with an additional liter of water decreased the electrolyte content of 1004 to less than one-fiftieth of its original value while reducing the electrolyte content of 1008 to less than one thirty-eighth of its original value.

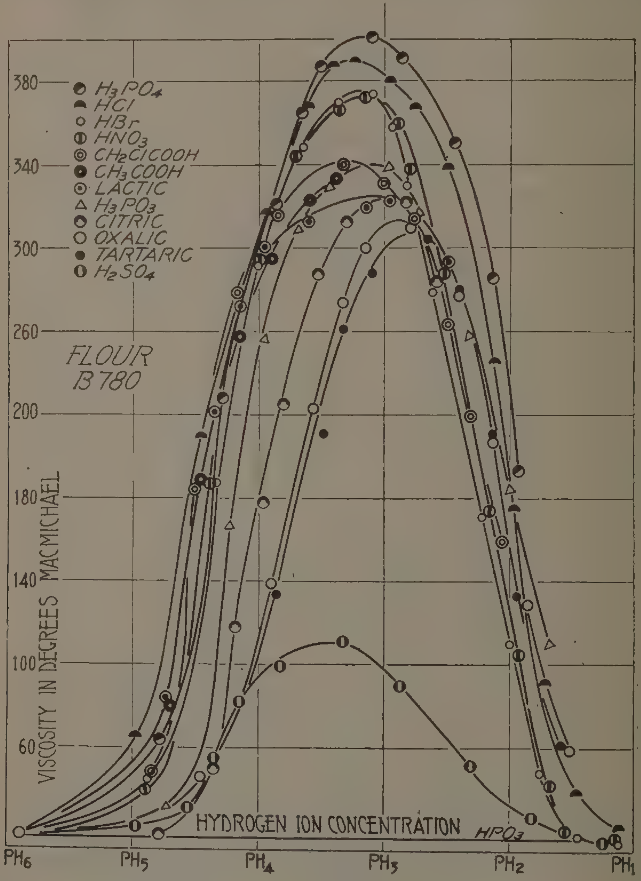

Fig. 6. Viscosity of Extracted Flour, 18 Grams of Extracted B-780 Made Up to 100 cc. and Treated with Different Amounts of Various Acids (Compare with Fig. 7.)

The ratio of the ash contents of the two flours is 1 to 1.77. The ratio of the conductivity of the first extracts is 1 to 1.58, of the second extracts 1 to 1.55, and of the third extracts 1 to 1.21. The results obtained in the viscosity measurements are the same, within experimental error, whether extracted with one liter of water or with two. That is, the actual content of the electrolytes was so small that changing the ratio from 1 to 1.55 to 1 to 1.21 and decreasing their amounts from 2.5 to 3.2 times seemed to make no appreciable difference in the viscosity readings. These results were therefore taken to indicate that the effect of salts on imbibition could be eliminated by digesting with one liter of water and discarding the extract. Later results seem to indicate that this is not strictly true, but that subsequent extraction may cause some increase in viscosity.

EFFECT OF VARIOUS CONCENTRATIONS OF DIFFERENT ACIDS ON VISCOSITY OF EXTRACTED FLOURS

The test showing the effect of the various acids on viscosity was repeated, using 18 grams of flour on the dry basis, extracting one hour with occasional shaking with one liter of water, centrifuging, discarding the extract, and making the residue up to a total volume of 100 cc. The results are recorded in Table IX and expressed graphically in Figures 6 and 7. The values obtained for the hydrogen-ion concentrations given in Table IX and Figures 6 and 7 were not obtained in the same way as were those given in Tables III and V. The quantity of flour was too small to use the previous method, therefore the expedient

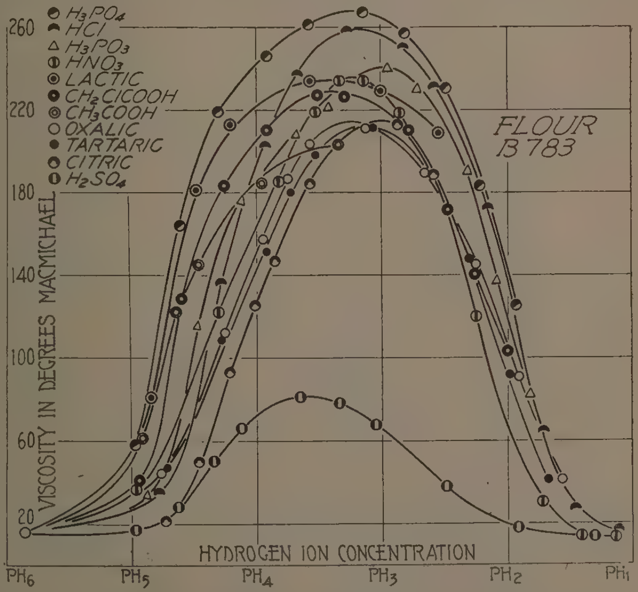

Fig. 7. Viscosity of Extracted Flour, 18 Grams of Extracted B-783 Made Up to 100 cc. and Treated with Different Amounts of Various Acids (Compare with Fig. 6.)

was adopted of using a Hildebrand electrode and measuring the hydrogen-ion concentration after the addition of each amount of acid. For this purpose 1.8 grams of flour on the dry basis was treated with 100 cc. of water with occasional shaking for one hour, centrifuged, the supernatant liquid decanted, and the residue made up to a total volume of 10 cc. A large funnel whose stem had been cut off and closed with a rubber stopper was used for the electrode vessel. This prevented the escape of froth which was constantly broken down with a stirring rod and permitted the use of a small volume of liquid. Instead of using normal acid solutions for the first additions, one-tenth normal solutions were used until a total of one cc. had been added, from then on normal acid was added. As far as could be detected this additional dilution did not affect the hydrogen-ion concentration. The results in this case are not as accurate as in the previous set but are probably correct to within 0.05 pH.

TABLE IX

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by Addition of Various Amounts of Normal Acid Solution, with the pH of Resulting Mixture*

The water soluble substances present in the natural flour were largely removed by digesting 18 grams of flour on the dry basis with 1000 cubic centimeters of distilled water for one hour at 25° C., with occasional shaking. The supernatant liquid was removed by centrifuging and the material remaining was made up to a volume of 100 cubic centimeters with distilled water. The viscosity values have all been corrected for dilution back to the original volume of 100 cubic centimeters. All determinations were carried out at the temperature of 25° C. The wire in this case was standardized with a 60 per cent sucrose solution whose absolute viscosity is 43.86 centipoise. This solution gave a reading of 87.7 degrees MacMichael.

cc. of N. acid added	Hydrochloric acid				Nitric acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	20	5.88	18	5.85	20	5.87	18	5.82
0.10	65	4.97	35	4.77	43	4.87	38	4.94
0.20	209	4.45	136	4.29	187	4.38	122	4.31
0.30	318	3.92	202	3.92	295	3.99	185	3.82
0.40	367	3.60	237	3.67	345	3.69	219	3.53
0.50	387	3.40	252	3.50	367	3.35	234	3.35
0.60	389	3.23	258	3.28	373	3.11	234	3.16
0.70	380	2.94	257	3.03	359	2.89	229	2.99
0.80	367	2.74	250	2.82	338	2.79	218	2.86
1.00	338	2.48	231	2.57	288	2.52	192	2.62
1.50	245	2.11	172	2.15	174	2.16	120	2.25
2.00	174	1.97	122	1.94	105	1.93	72	1.96
3.00	91	1.71	64	1.71	42	1.67	30	1.72
5.00	38	1.45	27	1.44	20	1.55	14	1.40
10.00	21	1.12	16	1.10	16	1.15	14	1.13

* Mr. Axel Olsen kindly assisted in making some of the viscosity determinations reported in this table.

TABLE IX—*Continued*

cc. of N. acid added	Oxalic acid				Tartaric acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	18	5.90	18	5.78	17	5.92	18	5 80
0.10	...	...	...	...	...	...	...	...
0.20	46	4.46	45	4.75	46	4.43	45	4.73
0.30	...	...	...	...	...	...	...	...
0.40	139	3.90	112	4.26	134	3.84	109	4.28
0.50	...	...	...	...	...	...	...	...
0.60	223	3.57	157	3.94	211	3.47	151	3.91
0.70	...	...	...	...	...	...	...	...
0.80	274	3.33	186	3.75	261	3.33	180	3.72
1.00	300	3.14	203	3.57	288	3.09	198	3.53
1.50	310	2.77	211	3.11	305	2.64	211	3.09
2.00	277	2.40	189	2.64	278	2.37	189	2.67
3.00	208	2.13	145	2.25	210	2.13	146	2.30
5.00	129	1.86	91	1.91	133	1.94	92	1.98
10.00	59	1.52	41	1.56	61	1.57	41	1.67

cc. of N. acid added	Ortho-phosphoric acid				Acetic acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	20	5.92	17	5.78	16	5.90	15	5.78
0.10	...	...	...	...	...	...	...	...
0.20	64	4.77	58	4.97	80	4.68	61	4.92
0.30	...	...	...	...	...	...	...	...
0.40	228	4.29	164	4.62	187	4.45	122	4.65
0.50	...	...	...	...	...	...	...	...
0.60	320	3.85	219	4.31	226	4.29	145	4.46
0.70	...	...	...	...	...	...	...	...
0.80	365	3.65	246	3.92	...	...	...	...
1.00	387	3.50	261	3.58	258	4.16	165	4.28
1.50	401	3.08	267	3.16	...	...	...	...
2.00	391	2.86	257	2.82	294	3.85	184	3.96
3.00	350	2.43	230	2.49	...	...	...	...
5.00	285	2.13	183	2.22	323	3.57	203	3.60
10.00	193	1.91	125	1.93	333	3.38	203	3.35

cc. of N. acid added	Citric acid				Phosphorous acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	16	5.87	17	5.82	16	5.87	17	5.78
0.10	...	...	...	...	...	...	...	...
0.20	18	4.77	21	4.72	32	4.72	35	4.85
0.30	...	...	...	...	...	...	...	...
0.40	50	4.35	50	4.46	167	4.23	116	4.48
0.50	...	...	...	...	...	...	...	...
0.60	118	4.18	93	4.21	257	3.94	176	4.11
0.70	...	...	...	...	...	...	...	...
0.80	178	3.96	125	4.02	309	3.67	208	3.67
1.00	225	3.80	147	3.85	329	3.43	221	3.42
1.50	288	3.52	184	3.57	339	2.96	240	2.96
2.00	313	3.30	198	3.31	317	2.71	230	2.72
3.00	...	...	...	...	258	2.33	190	2.33
5.00	322	2.82	213	2.87	184	2.01	137	2.08
10.00	285	2.57	189	2.60	110	1.67	82	1.81

TABLE IX—*Continued*

cc. of N. acid added	Monochlor acetic acid				Lactic acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	19	5.82	16	5.83	16	5.85	15	5.78
0.10	48	4.84	41	4.95	83	4.73	81	4.84
0.20	185	4.51	129	4.60	221	4.35	181	4.48
0.30	279	4.16	183	4.26	276	4.13	213	4.21
0.40	317	3.84	210	3.92	300	3.94	226	4.02
0.50	332	3.50	220	3.72	307	...	228	...
0.60	340	3.33	227	3.53	312	3.60	228	3.72
0.70	339	3.23	230	3.42	...	...	...	...
0.80	336	3.14	226	3.30	317	3.50	234	3.57
1.00	331	2.99	219	3.11	317	3.42	231	3.47
1.50	314	2.76	211	2.77	319	...	233	3.25
2.00	295	2.64	190	2.64	319	3.13	231	3.18
3.00	263	2.49	171	2.47	322	2.94	229	3.01
5.00	219	2.32	140	2.28	316	2.74	226	2.79
10.00	159	2.06	103	2.00	293	2.49	208	2.54

cc. of N. acid added	Sulfuric acid				Hydrobromic acid			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	18	5.87	17	5.78	18	5.87	...	...
0.10	22	4.97	17	4.97	45	4.88	...	...
0.20	31	4.56	28	4.63	187	4.35	...	...
0.30	55	4.36	50	4.36	293	4.01	...	...
0.40	82	4.14	66	4.13	348	3.64	...	...
0.50	99	3.82	76	3.89	370	3.36	...	...
0.60	107	3.57	81	3.64	374	3.08	...	...
0.70	111	3.33	79	3.48	358	2.93	...	...
0.80	106	3.18	78	3.35	330	2.81	...	...
1.00	90	2.87	68	3.06	279	2.62	...	...
1.50	52	2.32	38	2.49	171	2.22	...	...
2.00	38	2.10	27	2.20	110	2.00	...	...
3.00	27	1.81	18	1.91	48	1.76	...	...
5.00	...	...	...	...	17	1.45	...	...
10.00	15	1.25	14	1.30	15	1.15	...	...

cc. of N. acid added	Dichlor acetic acid	Trichlor acetic acid	Meta-phosphoric acid	
			Solution stood several months	Fresh solution
	B-780	B-780	B-780	B-780
	Viscosity	Viscosity	Viscosity	Viscosity
0.00	15	18	17	15
0.10	39	22	18	15
0.20	142	89	22	15
0.30	251	179	36	15
0.40	302	244	54	15
0.50	315	273	68	15
0.60	322	282	79	15
0.70	304	276	87	...
0.80	284	258	94	15
1.00	239	214	100	15
1.50	161	95	106	...
2.00	104	41	98	15
3.00	54	21	78	...
5.00	23	23	39	...
10.00	18	23	22	15

It is noted in Table IX and Figures 6 and 7 that the difference between flours B-780 and B-783 is not so marked as before and also that the imbibition of the various acids with a given flour reaches more nearly the same maximum, altho the differences between the two flours are still very great.

EFFECT OF SODIUM AND BARIUM HYDROXIDE ON VISCOSITY OF FLOUR SUSPENSIONS

The effect of sodium and barium hydroxide on the viscosity of these two flours was studied both with the soluble extract present and with the soluble extract partially removed by the method described above. The hydrogen-ion concentrations were determined with the Hildebrand electrode previously described. It is believed that the carbon dioxide of the air did not interfere with the determination of the hydrogen-ion concentration, but was swept away by the constant stream of hydrogen. Experiments in which the total amount of alkali was added all at once and the hydrogen-ion concentration measured immediately, gave practically the same results as those in which the alkali was added in small portions over a longer time. In the experiments with barium hydroxide, a saturated solution was used instead of a normal solution and the results were all calculated on the basis of a normal solution. The results obtained with the alkalies are

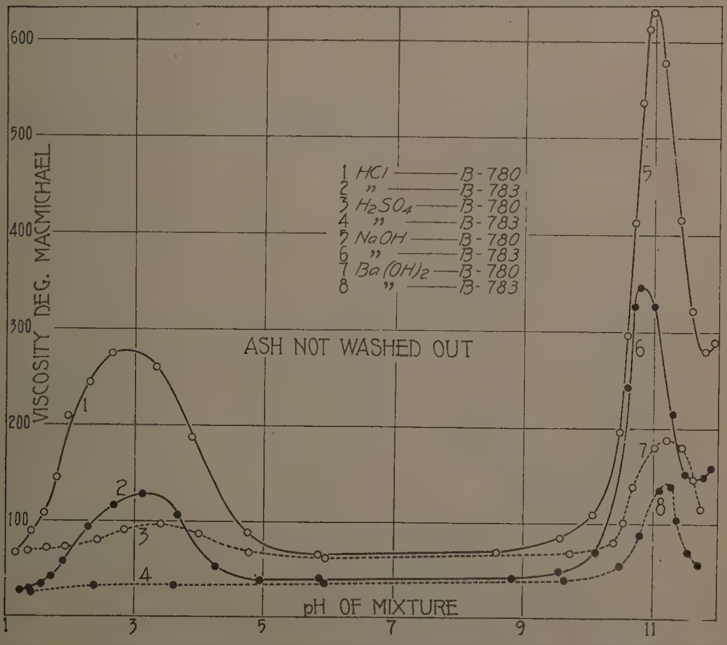

Fig. 8. Relation of Viscosity and Hydrogen-ion Concentration with Unextracted Flour

given in Table X and XI and Figures 8 and 9. For comparison over a range of pH, the effects of hydrochloric and sulfuric acids are also given in the figures.

TABLE X

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Sodium and Barium Hydroxide Solutions, with pH of Resulting Mixture*

Twenty-five grams of flour on the dry basis was taken in each instance, treated with 100 cubic centimeters of distilled water, and digested with occasional shaking at 25° C. for one hour. One hundred cubic centimeters of this mixture was taken for the viscosity measurements. All determinations were carried out at the temperature of 25° C., and are corrected for dilution back to the original volume of 100 cubic centimeters. The wire was standardized with a sucrose solution whose absolute viscosity was 5.73 centipoise. This solution gave a reading of 14.3 degrees MacMichael.

cc. of N. alkali added	Sodium hydroxide				Barium hydroxide			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	66	5.85	39	5.85	61	5.92	39	5.82
0.20	66	...	39	...	61	...	...	...
0.40	66	...	39	...	62	...	39	...
0.80	67	8.62	39	...	63	...	40	...
1.00	79	...	40	...	...	...	...	...
1.20	83	9.57	40	8.84	67	...	41	...
1.60	106	10.08	47	9.55	66	9.72	39	...
2.00	194	10.47	66	10.13	76	10.40	40	9.65
2.25	293	10.62	98	...	97	10.55	...	...
2.50	409	10.72	158	...	119	...	51	10.50
2.75	532	10.82	239	10.57	137	10.67	...	...
3.00	609	10.90	321	10.67	152	...	87	10.79
3.25	625	10.97	342	10.79	...	...	...	...
4.00	573	11.16	321	11.02	177	11.02	134	11.12
5.00	411	11.41	211	11.31	185	11.21	140	11.28
6.00	317	11.58	150	11.51	177	11.45	102	11.36
8.00	277	11.78	145	11.80	144	11.58	68	11.56
10.00	287	11.94	155	11.92	114	11.75	55	11.70

* In case of barium hydroxide it was, of course, necessary to use a more dilute solutio The data have all been calculated back to the basis of a normal solution.

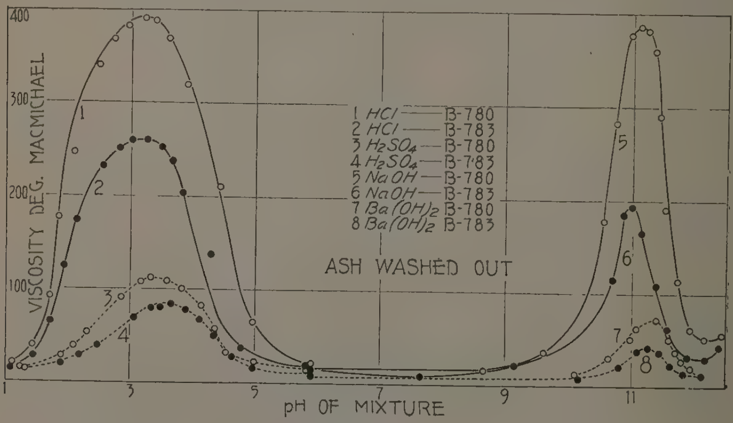

Fig. 9. Relation of Viscosity and Hydrogen-ion Concentration with Extracted Flour

TABLE XI

Viscosity, in Degrees MacMichael, of Flours B-780 and B-783 as Influenced by the Addition of Various Amounts of Normal Sodium and Barium Hydroxide Solutions, with the pH of the Resulting Mixture*

The water soluble substances present in the natural flour were largely removed by digesting 18 grams of flour on the dry basis with 1000 cubic centimeters of distilled water for 45 minutes at 25° C. with occasional shaking. The supernatant liquid was removed by decantation, the residue was treated with 500 cubic centimeters of distilled water, shaken, allowed to stand 15 minutes, and the decanted material remaining was made up to a volume of 100 cubic centimeters with distilled water. The viscosity values have all been corrected for dilution back to the original volume of 100 cubic centimeters. All determinations were carried out at the temperature of 25° C. The wire in this case was standardized with a 60 per cent sucrose solution whose absolute viscosity is 43.86 centipoise. This solution gave a reading of 87.7 degrees MacMichael.

cc. of N. alkali added	Sodium hydroxide				Barium hydroxide			
	B-780		B-783		B-780		B-783	
	Visc.	pH	Visc.	pH	Visc.	pH	Visc.	pH
0.00	15	...	9	...	15	...	9	...
0.20	15	8.66	9	7.64	15	...	9	...
0.40	36	9.62	21	9.16	15	...	9	...
0.80	177	10.55	116	10.68	15	10.09	9	10.14
1.00	282	10.72	184	10.85	...	...	...	...
1.20	339	...	194	11.02	32	10.63	22	10.80
1.40	378	10.94	...	...	...	...	...	...
1.60	387	11.11	164	11.11	50	10.97	39	11.06
1.80	381	11.23	...	...	...	...	...	...
2.00	358	11.34	107	11.41	63	11.09	43	11.26
2.25	290	11.45	...	...	64	...	43	11.31
2.50	190	11.53	63	11.56	68	11.28	...	...
3.00	112	11.75	42	11.72	73	11.39	38	11.45
4.00	62	11.92	33	11.87	51	11.58	22	11.61
5.00	...	...	...	...	38	11.70	...	...
6.00	51	12.16	31	12.17	27	11.78	16	11.83
8.00	...	...	...	...	21	11.94	...	...
10.00	55	12.41	44	12.41	14	12.10	14	12.10

* In case of barium hydroxide it was, of course, necessary to use a more dilute solution. The data have all been corrected back to the basis of a normal solution, however.

MAXIMUM VISCOSITY OBTAINED WITH LACTIC ACID USING A SERIES OF DIFFERENT FLOURS

The determination of viscosity with the salts partially removed probably represents more nearly the actual imbibitional powers of the proteins present in the flour. This is essentially a study of gluten, and hence those variables in its environment (such as electrolytes) which affect gluten properties should be removed, or rendered uniform. The ash content of flours (even of the higher grades) is so variable as to occasion corresponding variations in the imbibitional properties of the gluten, and the soluble ash components should accordingly be removed before gluten comparisons are attempted. It was therefore thought probable that some relation could be found between the viscosity values of flours and their baking strength. Lactic acid is probably the one best suited for this study because it maintains approximately maximum viscosity over a wide range of acid concentration (see Figures 1 and 2). Mr. Marshall, of the United States Bureau of Markets, kindly supplied a series of flours for this study, together with the baking and analytical data. The high points of the curve reached by the addition of increasing amounts of lactic acid were determined both with and without the removal of the water-soluble extract. These data and the baking and analytical data supplied by Mr. Marshall, are given in Table XII.

It is to be regretted that the viscosity data in some instances may not be the exact values, for there was not enough flour in most cases to run duplicate determinations.

EFFECT OF CONCENTRATION OF FLOUR ON VISCOSITY

In this study 12, 15, 18, 21, and in some instances 24 grams of flour on the dry basis were made up to 100 cc. with distilled water, allowed to stand 1 hour, and the increase in viscosity produced by the addition of various amounts of concentrated syrupy lactic acid was determined. The highest viscosity obtained by the addition of lactic acid is given in Table XIII, together with the actual grams of crude protein and of glutenin contained in the portions of flour used. This table is also made to include the grams of crude protein and glutenin in the portions of flour used in Table XV.

It was found that if the logarithms of the viscosity readings were plotted as ordinates and the logarithms of the flour concentration as abscissa, straight lines were obtained, as shown in Figure 10. Figure 10 also contains the logarithms of the viscosity readings plotted against the logarithms of the crude protein content and the glutenin content of the portions of flour used.

It will be observed from Figure 10 that the lines do not all lie at the same angle with respect to the axis of abscissa.

The equation for the logarithmic curve is

$$\text{log. viscosity} = a + b\ (\text{log. concentration})$$

where a is the logarithm of the viscosity reading when log. of concentration is zero; and b is the tangent of the angle made by the logarithmic curve with the axis of abscissa. The equation may also be expressed in the following form:

$$\text{Viscosity} = a\ (\text{concentration})^{b}$$

The constants a and b were calculated from the data by the method of least squares. The values of the constant b were also measured from the curve. The results of these calculations are given in Table XIV.

TABLE XII

ANALYSES OF FLOUR SAMPLES REPRESENTING TWO RANGES OF CRUDE PROTEIN CONTENT

The flours are arranged within each group in the order of their loaf volume. The highest viscosity obtained with lactic acid, both with and without the removal of the soluble salts, is given in the last two columns. The milling, baking, and analytical data were supplied by Mr. Marshall.

Lab. No.	U. S. supervisor's grade	Straight flour yield, %	Water absorption, %	Loaf volume cc.	Weight of loaf, gms.	Color of bread, score	Texture of bread, score	Protein (N X 5.7) 13.5 % moisture		Ash in flour %	M.° extract removed*	M.° extract present*
								% in wheat	% in flour			
				11% to 12% crude protein in flour								
6905	5 Dark Northern Spring....	67.2	61.5	2400	507	93.0	83.0	15.7	11.4	0.52	515	247
6632	Hard Red Winter........	74.5	58.8	2270	493	94.5	95.0	12.4	11.3	0.48	338	151
6806	2 Hard White	69.4	60.0	2210	503	90.0	90.0	12.4	12.0	0.48	294	97
6727	5 Dark Northern Spring....	62.7	57.9	2180	498	90.5	91.5	10.8	11.9	0.46	382	122
6918	3 Dark Hard Winter......	70.0	66.5	2170	522	94.0	94.0	14.7	11.2	0.41	454	269
6584	Hard Winter	69.1	58.5	2160	500	87.5	91.0	12.3	11.2	0.43	257	136
6982	1 Dark Northern Spring....	72.6	62.6	2120	517	88.5	90.0	13.3	12.0	0.46	368	194
7017	1 Dark Northern Spring....	74.1	60.6	2110	509	92.0	90.0	12.9	11.5	0.46	375	187
6989	1 Dark Northern Spring....	73.4	60.6	2100	511	90.5	88.5	12.5	11.3	0.49	356	145
6725	3 Dark Northern Spring....	67.1	56.5	2090	497	87.0	92.0	11.7	11.4	0.42	393	121
6723	2 Dark Northern Spring....	70.9	55.6	1990	494	86.5	89.0	11.8	11.2	0.43	418	119
6857	3 Soft White	71.7	58.5	1980	502	89.0	88.0	13.7	11.7	0.40	312	112
6730	2 Amber Durum	73.7	64.7	1920	517	88.5	92.5	11.5	11.1	0.68	204	47
6769	2 Dark Hard Winter......	72.4	60.9	1870	512	91.0	87.5	14.9	11.8	0.43	430	145
				8% to 9% crude protein in flour								
6960	1 Hard Winter	70.2	62.1	2290	501	93.5	92.8	12.1	8.1	0.46	311	135
6965	5 Hard Winter	71.9	60.9	2210	498	88.5	87.0	12.5	9.0	0.57	334	147
6966	2 Dark Hard Winter......	71.7	62.4	2170	506	92.0	92.0	12.9	8.8	0.53	391	166
6977	1 Hard Winter	74.3	61.5	2140	506	92.5	91.5	11.7	8.7	0.52	264	155
6649	1 Mixed	71.3	58.8	2040	510	95.0	89.5	10.0	8.9	0.46	263	96
6641	1 Soft White	75.5	61.2	2010	514	95.0	88.5	9.3	8.3	0.51	263	81
6642	1 Hard White	75.5	63.5	1990	513	95.0	86.5	9.9	8.6	0.54	215	66
6643	1 Soft White	76.5	55.9	1980	493	90.0	86.5	9.2	8.0	0.47	157	50
6637	1 Hard Winter	75.4	59.1	1920	507	91.5	88.5	8.9	8.2	0.49	274	89
7056	1 Soft White	70.1	57.1	1920	497	91.5	91.5	10.0	8.9	0.47	170	66
7054	2 Hard White	74.7	65.3	1890	516	90.0	89.0	8.9	8.5	0.68	320	67

* M,° signifies readings in degrees MacMichael.

TABLE XIII

Highest Viscosity Reached by Suspensions of Different Amounts of Various Flours on the Addition of Concentrated Syrupy Lactic Acid, Together with the Grams of Crude Protein and Glutenin Contained in the Indicated Portions of Flour

The weighed portions of flour on the dry basis were made up to a total volume of 100 cc. with distilled water and digested with occasional shaking for 1 hour before the determinations were made. The determinations were all made at 25° C. A 60 per cent sucrose solution gave a viscosity reading of 29.2° M. with the setting of the wire used.

Flour Lab. No.	6 gms. flour		9 gms. flour		12 gms. flour		
	Protein, grams	Glutenin, grams	Protein, grams	Glutenin, grams	Protein, grams	Glutenin, grams	Viscosity, M°
1001	0.763	0.342	1.144	0.513	1.525	0.684	17
1002	0.874	0.393	1.312	0.590	1.748	0.786	19
1003	0.599	0.251	0.898	0.377	1.198	0.503	6
1004	0.843	0.367	1.265	0.550	1.686	0.733	7
1005	0.738	0.326	1.106	0.489	1.475	0.652	21
1006	0.804	0.329	1.205	0.493	1.607	0.658	30
1007	0.941	0.388	1.411	0.583	1.882	0.776	20
1008	1.027	0.447	1.540	0.671	2.053	0.894	36
1009	0.925	0.414	1.387	0.622	1.849	0.830	32
1010	0.699	0.303	1.049	0.455	1.398	0.606	10
1011	0.720	0.296	1.080	0.444	1.440	0.592	8

Flour Lab. No.	15 gms. flour			18 gms. flour		
	Protein, grams	Glutenin, grams	Viscosity, M°	Protein, grams	Glutenin, grams	Viscosity, M°
1001	1.907	0.855	40	2.288	1.026	79
1002	2.186	0.983	34	2.623	1.179	57
1003	1.497	0.629	12	1.796	0.754	21
1004	2.108	0.917	13	2.529	1.100	24
1005	1.844	0.815	40	2.212	0.977	67
1006	2.009	0.822	67	2.410	0.986	106
1007	2.352	0.971	41	2.822	1.165	74
1008	2.567	1.118	65	3.080	1.341	106
1009	2.312	1.038	72	2.774	1.246	136
1010	1.748	0.758	21	2.097	0.909	37
1011	1.800	0.740	15	2.160	0.887	25

Flour Lab. No.	21 gms. flour			24 gms. flour		
	Protein, grams	Glutenin, grams	Viscosity, M°	Protein, grams	Glutenin, grams	Viscosity, M°
1001	2.669	1.197	135	....	....	..
1002	3.060	1.376	85	....	....	..
1003	2.096	0.880	32	2.395	1.006	49
1004	2.951	1.283	33	3.372	1.466	50
1005	2.581	1.140	104	2.950	1.303	140
1006	2.812	1.151	169	....	....	..
1007	3.293	1.359	109	....	....	..
1008	3.593	1.565	158	....	....	..
1009	3.236	1.453	198	....	....	..
1010	2.447	1.061	53	2.796	1.212	83
1011	2.520	1.035	39	2.880	1.183	55

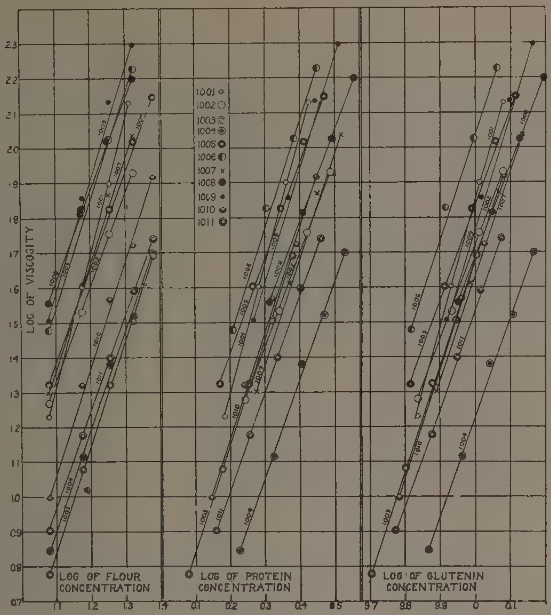

Fig. 10. A. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Flour Concentration of Unextracted Flour
B. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Protein Concentration of Unextracted Flour
C. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Glutenin Concentration of Unextracted Flour

TABLE XIV

Constants for the Logarithmic Expression: Log Viscosity $= a + b$ (Log Concentration) with the Salts Present

The calculated values were obtained by the method of least squares, the values for *a* are given on the basis of flour concentration, crude protein concentration, and glutenin concentration. The measured values for *b* obtained by the graphical method are also given.

Flour Lab. No.	Measured value of b	Calculated values			
		b	Flour conc. a	Protein conc. a	Glutenin conc. a
1001	3.647	3.705	—2.671	—0.558	—1.848
1002	2.662	2.689	1.799	0.570	1.555
1003	2.980	3.013	2.469	0.547	1.685
1004	2.852	2.829	2.184	0.207	1.232
1005	2.691	2.766	1.654	0.864	1.845
1006	2.955	2.996	1.731	0.883	2.048
1007	3.043	3.052	1.982	0.473	1.646
1008	2.620	2.643	1.295	0.732	1.686
1009	3.341	3.291	2.028	0.645	1.791
1010	2.858	3.005	2.227	0.578	1.669
1011	2.729	2.797	2.114	0.461	1.542

The effect of the removal of the soluble materials on the change in viscosity with concentration was also determined. For this purpose 6, 9, 12, 15, 18, and in some instances 21 grams of flour on the dry basis was digested with one liter of water, with occasional shaking, for 45 minutes, and then allowed to stand until the material had settled, from 5 to 15 minutes. The supernatant liquid was decanted and the residue made up to a volume of 500 cc. with distilled water, shaken, and the material allowed to settle. The supernatant liquid was again decanted and the residue made up to a total volume of 100 cc. and the maximum viscosity attainable with normal lactic acid determined. This substitution of simple decantation for the longer and more tedious procedure of removing the supernatant liquid by means of the centrifuge was adopted only after it was found that the two methods gave results which agreed within experimental error. Duplicate determinations were made throughout. The highest viscosity obtained by the addition of various amounts of normal lactic acid is given in Table XV.

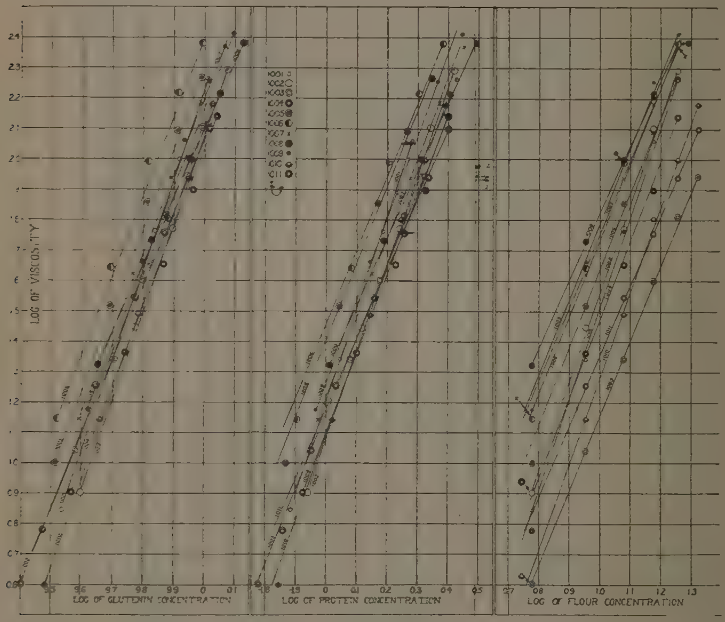

Fig. 11. A. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Glutenin Concentration of Extracted Flour

C. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Protein Concentration of Extracted Flour

B. Logarithms of Highest Viscosity Reading Produced with Lactic Acid Plotted Against Logarithms of Flour Concentration of Extracted Flour

The data in Table XV are expressed in the form of logarithmic curves in Figure 11. In this figure the logarithms of the viscosity as ordinates are plotted against three different abscissa, namely, the logarithms of the flour concentration, of the grams of crude protein present, and of the grams of glutenin present in the portions of flour used. It will be noted that using the glutenin concentration as well as the protein concentration as abscissa produces a closer grouping of the lines indicating the relationship of these components to the imbibition phenomena. It will be noted that the curves with the salts removed lie more nearly at the same angle than is the case with the salts present.

In Table XVI are given the values for the constant *b* measured from the curves, and the values for *b* and *a* calculated by the method of least squares.

TABLE XV

Effect of Concentration of Flour-in-Water Suspensions on Viscosity

The water soluble substances were removed by digesting the amounts of flour indicated with one liter of distilled water for 45 minutes, decanting the supernatant liquid, shaking with an additional 500 cc. of distilled water, decanting the supernatant liquid, and making the residue up to a total volume of 100 cc. A correction was made for dilution in the viscosity determinations. A 60 per cent sucrose solution having a viscosity of 43.86 centipoise gave a reading of 29.2 degrees MacMichael.*

Flour Lab. No.	6 gms. flour M°	9 gms. flour M°	12 gms. flour M°	15 gms. flour M°	18 gms. flour M°	21 gms. flour M°
1001	7	22	58	115	183	...
1002	8	28	59	127	196	...
1003	4	11	22	40	65	88
1004	8	23	45	79	138	...
1005	10	33	72	124	185	...
1006	14	44	98	165	240	...
1007	14	42	87	153	234	...
1008	21	54	100	163	240	...
1009	15	46	100	180	258	...
1010	4	14	31	64	100	152
1011	6	18	35	57	87	126

* Altho the 60 per cent sucrose solution had the same reading in this table as in Table XIII, a resetting of the wire was made and it is doubtful whether a comparison other than of a relative nature is justified.

Baking data.—The flours used in this work, laboratory Nos. 1001 to 1011, were subjected to a joint investigation by Rumsey (1922), Collatz (1922), and the author. The source, type, and class of the wheat and the grade of the flour are given in Table XVII.

TABLE XVI

Constants for the Logarithmic Expression: Log. Viscosity$=a+b$ (Log. Concentration) with the Salts Removed

The calculated values were obtained by the method of least squares, the values for a are given on the basis of flour concentration, crude protein concentration, and glutenin concentration. The measured values for b obtained by the graphical method are also given.

Flour Lab. No.	Measured value of b	Calculated values			
		b	Flour conc. a	Protein conc. a	Glutenin conc. a
1001	3.048	3.023	−1.515	+1.193	+2.244
1002	2.954	2.926	+1.365	1.083	2.099
1003	2.492	2.499	1.352	1.157	2.099
1004	2.551	2.552	1.085	1.092	2.011
1005	2.631	2.666	1.048	1.378	2.325
1006	2.654	2.610	0.861	1.418	2.431
1007	2.565	2.568	0.840	1.226	2.213
1008	2.206	2.212	0.396	1.306	2.107
1009	2.678	2.622	0.848	1.281	1.195
1010	2.893	2.909	1.645	1.071	2.127
1011	2.304	2.398	1.062	1.148	2.073

TABLE XVII

History and Description of Flour Samples

Flour Lab. No.	Locality where grown	Variety of wheat	Grade of wheat	Grade of flour
1001	Central Kansas Reno County	Turkey Red	Hard Red Winter	Patent
1002	Central Kansas Reno County	Turkey Red	Hard Red Winter	First clear
1003	Washington, Walla Walla	Little Club	White Club	Straight
1004	North Dakota Red River Valley	Marquis and Bluestem	Hard Red Spring	Second clear
1005	North Dakota Red River Valley	Marquis Bluestem	Hard Red Spring	Patent
1006	Canada, Southern Alberta	Marquis	Selected Hard Red Spring	Patent
1007	Canada, Southern Alberta	Marquis	Selected Hard Red Spring	First clear
1008	Canada, Saskat. Valley, Saskatoon	Marquis	Hard Red Spring	Patent
1009	Red River Valley	Marquis mostly	Hard Red Spring	Patent
1010	Utah, irrigated land	Kofod*		Straight
1011	Ohio, Williams County	Like Fultzo- Mediterranean	Soft Red Winter	Long patent

* Identified by J. Allen Clark, of the U. S. Department of Agriculture, as "probably Kofod." Rumsey (1922) and Collatz (1922) refer to this sample as "like Sonora, California wheats." Their identification is undoubtedly incorrect.

The baking data of the series are given in Table XVIII. The data are the result of several bakings in which each flour was baked in such a way as to produce the largest possible volume and at the same time make a loaf of bread that would be desirable commercially. The flours were baked and scored by three bakers over a period of approximately a year, with the same end in view. The results given in Table XVIII are selected with the belief that they represent the most trustworthy data obtained.

PROTEIN FRACTIONS IN THE VARIOUS FLOURS

Because of the slight solubility of gliadin in distilled water it was desirable to ascertain how much protein was removed by the treatment with one liter of water followed by a subsequent treatment with 500 cc. of water. Accordingly the following experiment was carried out. Duplicate portions of 18 grams and 9 grams, on the dry basis, of flour 1009 were treated with one liter of water with occasional shaking, for 45 minutes, the material was allowed to settle for 15 minutes, and the supernatant liquid was then decanted into a 2-liter flask. The residue was treated with 500 cc. of distilled water, shaken thoroly, and allowed to stand 15 minutes, then the supernatant liquid was decanted into the 2-liter volumetric flask, the flask was made up to the mark with water, and the protein content (N × 5.70) of an aliquot was determined by the Kjeldahl method.

The residue from this extraction was treated with 100 cc. of 95 per cent ethyl alcohol, the water already present in the residue being sufficient to dilute the alcohol so that the final concentration was approximately 70 per cent alcohol. This material was then digested for two hours with occasional shaking, at the end of which time it was centrifuged and the supernatant liquid decanted into a 500-cc. volumetric flask. The residue was then treated wih 100 cc. of 70 per cent alcohol and digested, with occasional shaking, for 30 minutes. At the end of this time it was centrifuged and the supernatant liquid decanted into the volumetric flask, the extraction of the residue with 100 cc. of alcohol was repeated and the extract added to the volumetric flask. The flask was then made up to volume and the protein content (N × 5.70) of an aliquot was determined by the Kjeldahl method.

The residue from the two extractions was treated with 50 cc. of 70 per cent alcohol, placed in a mechanical shaker, and shaken for 30 minutes. At the end of this time it was centrifuged and the protein content (N × 5.70) was determined by the Kjeldahl method. The residue was again extracted in a similar manner and the protein in the extract determined.

TABLE XVIII

Comparative Baking Tests of Flours*

Data were obtained from the American Institute of Baking, the final score being a summary of points according to the American Institute of Baking standards (1922).

Flour sample	Per cent absorption	Fermentation period, minutes	Proofing period, minutes	Weights in grams					Volumes cc.	Score
				Dough at mixing	Dough molded	Loaf hot	Loaf 1 hour	Loaf 18 hrs.		
1009	59	255	60	564	518	457	448	435	2160	100
1001	58	231	60	543	539	...	488	460	2010	99
1008	60	203	53	542	535	500	492	464	2000	97
1002	58	225	53	532	527	491	...	462	1880	95
1006	61	195	55	541	536	494	486	471	1735	91
1005	59	187	65	536	531	496	484	464	1820	90
1010	58	165	60	531	527	491	482	468	1760	83
1011	56	229	51	529	524	489	479	459	1720	76
1003	53	186	57	520	...	473	464	438	1650	63
1007	65	165	46	557	552	512	500	478	1460	46
1004	58	192	45	549	...	504	498	473	1415	35

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* These flours were subjected to a joint investigation by L. A. Rumsey, F. A. Collatz, and the author. The results of the investigation by Mr. Rumsey (1922) and Mr. Collatz (1922) are presented by them.

The residue remaining after this extraction was treated twice with 50 cc. of 95 per cent ethyl alcohol by shaking in a mechanical shaker for 30 minutes and followed by a treatment with 50 cc. of ethyl ether. The protein content of these combined extracts was determined.

The final residue was allowed to dry in the air and was then treated with enough distilled water to make a total volume of 100 cc., and the effect of normal lactic acid on its viscosity was determined. The highest value obtained with the various amounts of lactic acid is given in Table XIX, together with the data on the protein extracted.

It will be noted that while the viscosity reached is not as high as that reached in the previous determination, i.e., 258° M., (cf. Table XV) the increase is of the same order of magnitude and confirmed earlier indications that the glutenin was mainly responsible for the imbibitional effects produced by the addition of acid.

In order to investigate this point still further, 18 grams of flour 1009 was shaken up with 500 cc. of distilled water, the flour particles allowed to settle for 15 minutes, and the supernatant liquid then decanted into a 2-liter volumetric flask. Extraction with 500 cc. of distilled water was repeated three times, making a total volume of 2 liters in four separate portions used for the extraction. The protein content (N × 5.70) was determined on an aliquot of the extract.

The residue from the above extraction was again extracted with 2 liters of distilled water in the way described and the amount of protein (N × 5.70) removed in this second extraction was determined by the Kjeldahl method.

The residue remaining after this extraction was treated with 100 cc. of 95 per cent ethyl alcohol, shaken in a mechanical shaker for one hour, centrifuged, and the extract decanted into a 500-cc. volumetric flask. The residue was twice extracted with 100 cc. of 70 per cent ethyl alcohol and the protein content determined on an aliquot of the combined extracts.

The same procedure was repeated with a second sample of flour, except that 12 extractions with water were made previous to the alcohol extraction.

The same procedure was repeated with a third sample of flour, except that 16 extractions were made with water previous to the alcoholic extraction. The results are reported in Table XX together with the highest viscosity reached when the final residue, made up to 100 cc. with water, was treated with various amounts of lactic acid.

TABLE XIX

PROTEIN EXTRACTED FROM FLOUR 1009 BY VARIOUS METHODS

(1) One liter of water followed by 500 cubic centimeters of water, (2) residue extracted 3 times with 70 per cent alcohol, (3) sum of (1) and (2), (4) residue extracted with 50 cubic centimeters of 70 per cent alcohol, (5) residue extracted again with 50 cubic centimeters of 70 per cent alcohol, (6) residue extracted twice with 50 cubic centimeters of 95 per cent alcohol followed by 50 cubic centimeters of ether, (7) sum of protein extracted, (8) dry residue was made up with water to 100 cubic centimeters volume and the highest viscosity obtainable with lactic acid was determined. Wire read 29.2° M. with 60 per cent sucrose solution of viscosity 43.86 centipoise.

Weight of flour taken, grams	(1) Water extract, per cent	(2) First alcohol extract, per cent	(3) (1) + (2) per cent	(4) Second alcohol extract, per cent	(5) Third alcohol extract, per cent	(6) 95% alcohol ether extract, per cent	(7) Total protein extracted, per cent	(8) Viscosity reading, M°
18	3.93	5.16	9.09	0.19	0.13	0.02	9.43	191
18	4.66	4.33	8.99	0.18	0.14	0.02	9.33	195
9	5.88	3.22	9.10	0.17	0.13	0.02	9.42	...
9	6.04	2.83	8.87	0.17	0.11	0.01	9.16	...
		Average=	9.01			Average=	9.33	

Alcohol soluble protein A. O. A. C. method=9.04.

TABLE XX

Protein Extracted from Flour 1009 by Successive Treatments with Water Followed by Alcohol

Eighteen grams of flour was extracted four times with 500 cubic centimeters of water and the protein (N × 5.70) in the combined extract determined. The residue was then extracted again with water the number of times indicated, and finally three times with 70 per cent alcohol. The protein content of the various extracts was determined, the residue made up to 100 cubic centimeters, and the maximum increase with lactic acid determined. Wire used read 29.2° M. with a 60 per cent sucrose solution whose viscosity is 43.86 centipoise.

First 4 extracts, per cent protein	Second 4 extracts, per cent protein	Third 4 extracts, per cent protein	Fourth 4 extracts, per cent protein	Alcohol extracts, per cent protein	Total per cent protein extracted	Viscosity M°
6.67	1.61	...	...	1.85	10.13	*
6.77	1.56	0.75	...	1.25	10.33	157
6.77	1.43	0.63	0.52	1.12	10.33	149

* Residue lost by accident.

It will be seen from Table XX that the extraction with water apparently removed most of the alcohol soluble protein and that the greatest part is removed in the first four treatments with water. The residue did not exhibit as high a viscosity as the original flour when the soluble electrolytes were removed by the process first used, i.e., 258° M. (cf. Table XV). As a result of the treatment recorded in Table XX approximately one per cent more protein was removed than in the case recorded in Table XIX. This would account for the difference in viscosities recorded in the two tables. It was thought that this decrease in viscosity as shown in Tables XIX and XX as compared with Table XV might be due to the denaturizing effect on the glutenin of either the drying or the treatment with alcohol.

In order to investigate this point, 18 grams of flour 1009 was extracted eight times with 500 cc. portions of distilled water followed by three extractions with 70 per cent alcohol as described above, and the residue was then extracted with four additional portions of 500 cc. of distilled water. The amount of protein removed by this last extraction with water was 0.31 per cent. The highest viscosity reached with lactic acid was 202° M.

The procedure was repeated, except that the flour was first extracted with twelve portions of water instead of eight. The amount of protein extracted in the final treatment with water was 0.35 per cent. The highest viscosity reached was 160° M.

The experiment was repeated, except that the flour was first extracted with sixteen portions of distilled water. The protein content of the last water extract was 0.26 per cent, the highest viscosity reached was 105° M. It is rather difficult to interpret these results as, unfortunately, the amounts of protein extracted by the different treatments were not determined. It does seem to indicate that the treatment with alcohol markedly affects the imbibitional powers of the remaining protein or that the removal of that last portion of protein extracted with the alcohol decreases the imbibition.

An experiment performed with the expectation that it would throw some light on the subject was carried out as follows: 18 grams of flour 1009 was extracted with eight portions of distilled water. The residue was then made up to a total volume of 100 cc. and the effect of additions of various amounts of lactic acid was studied. The experiment was then repeated with 18-gram portions of flour which had been extracted twelve and sixteen times with water.

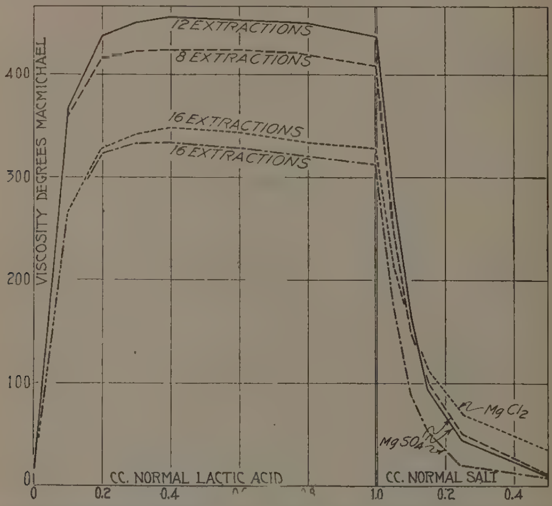

Fig. 12. Effect of Repeated Extraction of the Flour with Water on Viscosity as Influenced by Lactic Acid and Effect of Adding Salts to the System

It will be seen that this experiment is essentially the same as those already noted, except that treatment with alcohol is omitted. The results of the experiment are given in Table XXI and are shown graphically in Figure 12. The results point to some very interesting conclusions. Table XIX shows that eight extractions with water remove 8.28 per cent of protein, twelve extractions remove 9.08 per cent, and sixteen extractions remove 9.35 per cent. Subsequent experiments (Table XXII) indicate that the total sum of the albumen, globulin, and alcohol-soluble protein (gliadin) in sample No. 1009 is 8.49 per cent. It therefore appears that practically all the gliadin has been removed from this flour by repeated extraction with distilled water; nevertheless the maximum viscosity attained, i.e., 456° M., is much higher than any of the previous values, indicating that the gliadin is not responsible for change in viscosity on the addition of acids but that such changes are probably due almost entirely to the glutenin fraction. The effect of even 0.10 cc. of normal lactic acid is very pronounced, causing an increase in viscosity of more than 90 times the value obtained with distilled water (4° M. to 365° M.). The effect of electrolytes in depressing these high viscosities is equally pronounced, as can be seen from an inspection of Figure 12. We shall have occasion to return to this experiment later when we consider the nature of the mechanism involved in viscosity changes induced by the addition of acids and alkalies.

TABLE XXI

Viscosity, in Degrees MacMichael, as Affected by Lactic Acid, Obtained with 18 Grams of Flour 1009 by Treating the Residue Made Up to 100 Cubic Centimeters After Extracting 8, 12, and 16 Times with 500 cc. Portions of Distilled Water

After one cc. of lactic acid had been added, the material was treated with normal magnesium sulfate and in one case with magnesium chloride. The wire used read 29.2° M. with a 60 per cent sucrose solution whose viscosity was 43.86 centipoise.

cc. of N. solution added	8 extractions with 500 cc. of water	12 extractions with 500 cc. of water	16 extractions with 500 cc. of water	16 extractions with 500 cc. of water
		Lactic acid		
	M°	M°	M°	M°
0.00	4	4	3	3
0.10	360	365	265	264
0.20	415	436	322	328
0.30	422	452	332	342
0.40	424	456	333	349
0.60	425	453	327	343
0.80	418	449	320	333
1.00	408	439	312	327
	Salt solution added to material containing 1 cc. lactic acid			
	$MgSO_4$	$MgSO_4$	$MgSO_4$	$MgCl_2$
0.05	250	276	177	214
0.10	153	165	90	154
0.15	98	95	53	113
0.25	50	46	22	70
0.50	12	11	7	34

Acting on the hypothesis that the glutenin is the main protein concerned in the imbibition produced by acid and alkali, it appeared very desirable to determine the glutenin content of the flours investigated. As pointed out in the introduction, the accurate determination of the quantity of the various proteins in wheat flour presents unusual difficulties. The data presented in some of the preceding tables confirm this conclusion. In an attempt to determine the proportions of the various proteins in this series of flours, the following determinations were made. The protein content of the several fractions was calculated by multiplying the nitrogen content as determined by the Kjeldahl method by the factor 5.7.

Total protein.—The total protein was determined on a one-gram sample.

Potassium sulfate–soluble protein (A. O. A. C. method).—For this determination 6 grams of flour was extracted with 100 cc. of 5 per cent potassium sulfate solution by shaking in a mechanical shaking machine for one hour, filtering through a fluted filter, and determining the nitrogen content of a 50-cc. aliquot.

Alcohol-soluble protein (A. O. A. C. method).—In this determination 4 grams of flour was treated with 100 cc. of 70 per cent alcohol by shaking in a mechanical shaker for one hour, filtering the extract clear through a fluted filter, and determining the nitrogen content of a 50-cc. aliquot.

Potassium sulfate-soluble protein, second method.—This procedure was the same as the previous potassium sulfate extraction except that at the end of the shaking period the material was centrifuged and the volume of the supernatant liquid measured. The supernatant extract was then filtered through a fluted filter and the nitrogen in a 50-cc. aliquot determined.

Alcohol-soluble protein in the residue after extraction with potassium sulfate.—Enough alcohol was added to the residue after extraction with 5 per cent potassium sulfate solution to make a total volume of 150 cc. of 70 per cent alcohol, and the mixture was digested by shaking in the mechanical shaker for one hour. At the end of this time the material was allowed to settle and was then filtered clear through a fluted filter, and the nitrogen in a 50-cc. aliquot was determined.

In the case of all these filtrations the first portion of liquid running through the filter was returned to the filter.

All the above determinations were carried out in duplicate, and if the duplicates did not show close agreement the determination was repeated.

It was believed that the glutenin content would be represented most accurately by subtracting from the total protein content of the flour the sum of the amounts of protein extracted by 5 per cent potassium sulfate followed by 70 per cent alcohol. The A. O. A. C. method of determining glutenin in flour is to subtract from the total protein the sum of the potassium sulfate–soluble and alcohol-soluble protein as determined on different portions of flour. As these two solutions have been shown partially to extract the same material, the glutenin value obtained by this method is much too low.

TABLE XXII

PROTEIN FRACTIONS OF VARIOUS FLOURS IN TERMS OF PERCENTAGE OF TOTAL FLOUR ON DRY BASIS. ARRANGED IN ORDER OF THEIR LOAF VOLUME

(1) Lab. No.	(2) Loaf volume, cc.	(3) 5 per cent K_2SO_4 soluble protein, per cent	(4) 5 per cent K_2SO_4 soluble protein centrifuged, filtered, per cent	(5) Alcohol-soluble protein, per cent	(6) Alcohol-soluble after K_2SO_4 extraction, per cent	(7) Total protein content, per cent	(8) Dry hand-washed gluten, per cent	(9) Glutenin (7)− (4)+(6)], per cent
1009	2160	1.59	1.69	9.04	6.80	15.41	15.9	6.92
1001	2010	1.36	1.55	6.81	5.46	12.71	11.7	5.70
1008	2000	1.95	2.11	10.09	7.55	17.11	16.6	7.45
1002	1880	1.74	1.99	7.99	6.03	14.57	14.2	6.55
1005	1820	1.54	1.74	7.41	5.12	12.29	11.5	5.43
1010	1760	1.63	1.76	6.96	4.84	11.65	11.5	5.05
1006	1735	1.54	1.71	7.98	6.20	13.39	12.7	5.48
1011	1720	1.70	1.91	7.33	5.15	12.00	11.7	4.94
1003	1650	1.21	1.37	5.75	4.42	9.98	9.7	4.19
1007	1460	2.20	2.35	8.98	6.86	15.68	15.6	6.47
1004	1415	2.46	2.74	7.55	5.20	14.05	12.9	6.11

The results for the potassium sulfate–soluble protein by the two methods do not agree, altho the only difference in manipulation was filtration of the liquid in one instance, and the use of a centrifuge for a preliminary classification preceding filtration in the other. It is probable that in the case of filtration without centrifuging, the starch and suspended matter have not completely settled and the filters, therefore, clog and ultra-filter out some of the protein in solution. When the centrifuge is used, this suspended material is thrown down, thus preventing the clogging of the pores of the filter paper. There is a marked difference in the rate of filtration in the two instances, filtration being very much more rapid following centrifuging. These experiments indicate the desirability of carefully studying the methods for the determination of the amount of the various proteins in cereal products.

The data obtained are shown in Table XXII. The dry crude gluten, washed from the flour by hand, is included in this table.

EFFECT OF TEMPORARY CHANGES IN HYDROGEN-ION CONCENTRATION OF DOUGH ON COLLOIDAL PROPERTIES OF GLUTEN

The flour used in this experiment was a strong patent having an absorption of 56.2 per cent.[1] The amount of hydrochloric acid required to bring the dough to a pH of 3.0 and of sodium hydroxide to bring a dough to a pH of 11.0 was determined. These two hydrogen-ion concentrations were chosen because they were the points of maximum imbibition with acid and alkali respectively. Doughs were then made with water containing enough acid or alkali to give the one or the other of these hydrogen-ion concentrations, but the amount of water was restricted, so that when the acid or alkali was neutralized with an equivalent solution, the dough would contain the normal amount of water—56.2 per cent. The doughs were kept at these two different hydrogen-ion concentrations for 30 minutes and then the acid or alkali was neutralized, bringing the dough back as nearly as possible to its original hydrogen-ion concentration, and additional water was added to give the necessary dough consistency. The amount of sodium chloride formed by this neutralization was subtracted from the amount of salt added in the baking formula. The other ingredients of the dough were not added until after the acid or alkali had been neutralized. The baking formula and procedure used was that suggested by Bailey (1916). Two duplicate doughs were prepared in each case and a predetermined amount of takadiastase was added to one in order that the diastatic activity might not be a limiting factor. In another set of experiments one half the dough was brought to a pH of 3.0, the acid neutralized, and then the other half of the flour added.

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[1] The absorption of a flour is usually considered 56.2 per cent when 56.2 grams of water are added to 100 grams of air-dry flour to make a dough of the required consistency.

The actual absorption of a dough at a pH of 3.0 was determined and was found to be 61.3 per cent. While this is an increase of about 5 per cent over the control, nevertheless the increase is small compared with what might be expected from the viscosity curves. The reason for this small difference may be due to two causes: The inhibiting effect of the sodium chloride added in the baking formula, and the large amounts of imbibitional water which may not be held firmly enough to make a dough of the proper consistency. The results of the experiments are given in Table XXIII.

TABLE XXIII

EFFECT ON LOAF VOLUME OF TEMPORARILY CHANGING THE HYDROGEN-ION CONCENTRATION OF THE DOUGH

For each loaf 300 grams of flour was taken.*

Treatment of dough	Loaf volume, cc.	Absorption, per cent
Control	1600	56.2
To pH 3 and back	830	59.1
To pH 3 and back+diastase	1050	61.8
To pH 11 and back	1130	58.9
To pH 11 and back+diastase	1085	56.2†
Absorption determined at pH 3	....	61.3
New Baking		
Control	1425	56.8
Control+diastase	1390	57.2
Half of dough to pH 3 and back	1325	63.4
Half of dough to pH 3 and back+diastase	1345	63.9

* Mr. Arnold Johnson kindly carried out the bakings reported in this table.

† Amount of water restricted.

It will be noted that all the treatments decreased the loaf volume. The decrease is not so apparent in the second set of bakings. In this baking the control did not behave normally. This the baker attributed to the poor quality of the yeast used. The effect of the treatments was shown very markedly in the handling of the doughs. They were extremely short and broke like putty when pulled, while the baked bread had a very coarse texture. The loaves in which the hydrogen-ion concentration had been changed had practically white crusts, exhibiting no browning in the oven, altho the control loaves browned to an unusual extent. The addition of diastase did not alter this condition.

We have found in other experiments that the viscosity of a flour-in-water suspension at a pH of 11.0 decreases fairly rapidly with time of standing. Keeping a dough at a pH of 11.0 for 30 minutes may permit the alkali to exert its peptizing action on the gluten and thus destroy the colloidal properties which give the flour its desirable baking qualities. A flour-in-water suspension kept at a pH of 3.0 for one hour shows no appreciable change in viscosity due to standing, nevertheless a dough held at this hydrogen-ion concentration for 30 minutes lost its baking strength. At this hydrogen-ion concentration the gluten may have undergone changes of a nature similar to solution which would result in a decided change in its colloidal properties.

EFFECT OF TREATMENT WITH ALCOHOL ON COLLOIDAL CONDITION OF THE GLUTEN AS REFLECTED IN LOAF VOLUME

Gliadin has been universally regarded as an important factor in flour strength because whenever the gliadin has been removed from flour by extraction with alcohol and the resulting residue dried and remilled, the flour so obtained was found to have lost the capacity "for producing a bold, large-volumed, well-risen loaf."

Snyder (1897), Voorhees (1900), and Olson (1917) all demonstrated the loss in baking strength due to the removal of gliadin from the flour, but apparently no one of these observers tried the experiment of treating flour with alcohol and then drying, remilling, and baking the flour without removing the alcohol-soluble protein. Kosutány (1903) was able to obtain only 5.5 per cent of wet gluten of very poor quality from flour which had been simply treated with alcohol and then redried. The effect of alcohol on the colloidal properties of the glutenin as shown by the viscosity studies (cf. Tables XX and XXI) suggested the following experiment:

Doughs were prepared using 70 per cent and, in two instances, 95 per cent ethyl alcohol, 60 cc. of alcohol being added per 100 grams of flour. The doughs so prepared were crumbly and not coherent. As soon as the doughs were made, they were crumbled and placed on large glass plates. A current of air was blown over the material with an electric fan and it was continuously crumbled and stirred. The flour was to all appearances dry within an hour, the drying taking place at a temperature not exceeding 25° C. The material so obtained was remilled in an experimental flour mill and baked. Check samples of normal untreated flour were baked at the same time. The experiment was carried out with the patent flour used in the experiments reported in Table XXIII and with samples of both durum and rye flours. The rye flour contains no protein which responds in any appreciable degree to the imbibitional effect of acids, and it was chosen because it was believed that if flour strength was associated with the colloidal condition of the glutenin, treatment with alcohol would not affect the baking qualities of the rye flour to an appreciable extent. The results obtained are given in Table XXIV. Photographs of the resulting loaves are shown in Plates I and II.

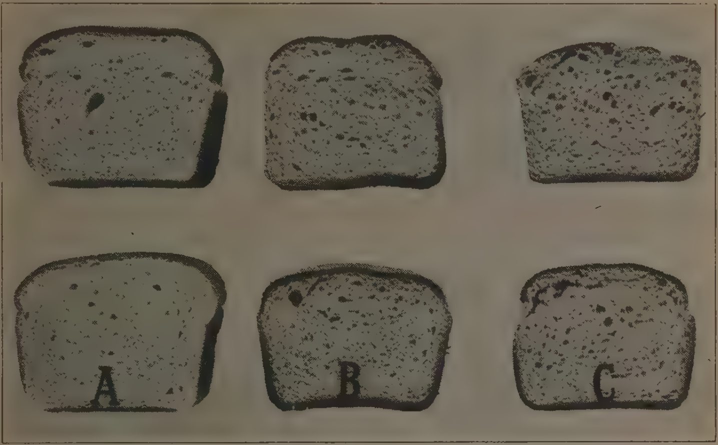

Plate 1. Effect of Alcohol Treatment on Baking Qualities of Wheat Flour (See Table XXIV.)
A. Check, normal flour.
B. Flour doughed 95% alcohol, dried, remilled, and baked.
C. Flour doughed 70% alcohol, dried, remilled, baked.

TABLE XXIV

EFFECT ON BAKING STRENGTH OF FLOUR OF PREPARING DOUGHS WITH ALCOHOL, IMMEDIATELY DRYING AT 25°C., REMILLING, AND BAKING

The controls in each case were normal, untreated flours*

Kind of flour	Conc. of alcohol, per cent	Diastase added	Loaf volume, cc.	Absorption, per cent
White flour control	..	No	1425	56.8
White flour control	..	Yes	1390	57.2
White flour	95	No	1170	59.2
White flour	95	Yes	1230	60.3
White flour	70	No	1235	60.6
White flour	70	Yes	1190	58.8
Durum control	..	No	1605	58.6
Durum control	..	Yes	1515	58.1
Durum	70	No	1280	66.9
Durum	70	Yes	1205	66.9
Rye control	..	No	1145	52.0
Rye control	..	Yes	1160	52.0
Rye	70	No	1310	55.4
Rye	70	Yes	1300	55.4

* Mr. Arnold Johnson kindly carried out the bakings reported in this table.

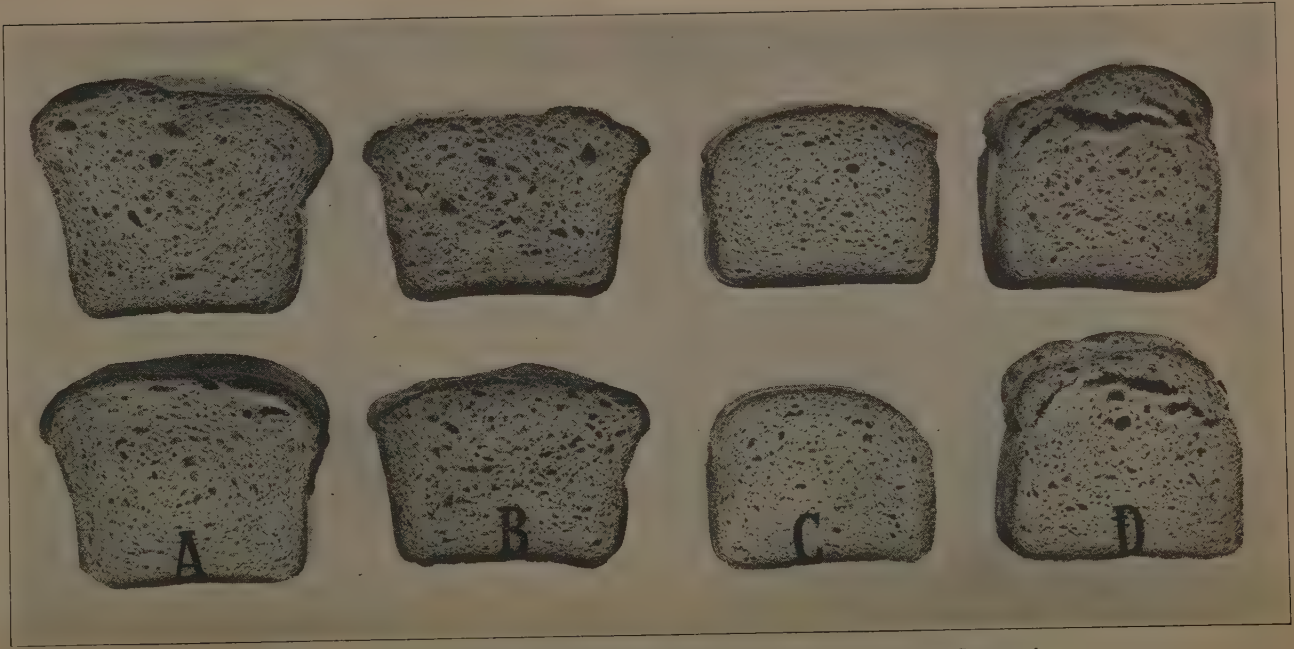

Plate II. Effect of Alcohol Treatment on Baking Qualities of Durum Wheat Flour as Contrasted with Rye Flour (See Table XXIV for data.)

A. Check loaf, durum flour.
B. Durum doughed 70% alcohol, dried, remilled, and baked.
C. Rye check.
D. Rye doughed 70% alcohol, dried, remilled, and baked.

Fermentation progressed at an apparently normal rate in the doughs which had been previously treated with alcohol, altho after the first punch they did not rise as high as the controls. The alcohol-treated patent flour and durum flour doughs were hard to handle; they were short and puttylike and broke in the kneading process. Of the rye flour doughs, no difference could be detected between the control doughs and those made from alcohol-treated flour.

Small open craters were formed toward the end of the fermentation of the alcohol-treated doughs, owing to the loss of carbon dioxide through the surface of the fermenting mass. These craters did not close after forming, and the surface of the doughs looked as if perforated with a blunt instrument.

These experiments are taken as rather definite proof that the colloidal properties of the gluten are extremely important in the baking quality of a flour. In these experiments no material was removed from the flour, the flour was left in its original condition as nearly as possible with the exception of changes in its colloidal properties. The amount and relative proportions of the various components are apparently not disturbed. The effect of alcohol was not due to solution of the gliadin, as is shown by the fact that the same deleterious results were produced by 95 per cent alcohol, in which concentration of alcohol gliadin is insoluble. The results obtained in the viscosity experiments indicate that the effect of alcohol may be attributed to change in the colloidal condition of the glutenin.

DISCUSSION

METHODS AND GENERAL OBSERVATIONS

The method adopted in this investigation for the study of the imbibitional power of the proteins in wheat flour was to measure the viscosity of flour-in-water suspensions, and the changes in viscosity produced by various treatments.

At the beginning of the investigation it was found that the viscosity of such suspensions was very sensitive to mechanical treatment, the mere repeating of the viscosity determination with the same sample time after time causing a marked decrease in its viscosity. While this behavior was in agreement with the findings of numerous other investigators, it rendered the investigation more difficult and probably influenced to some extent the accuracy of the results. The viscosity of the suspensions was found to change with time of standing, this being especially noticeable in cases in which the suspension had been treated with acids or alkalies. In an effort to minimize the effect of these factors, the time and mechanical treatment procedures were standardized as much as possible. The Ostwald viscosimeter did not lend itself readily to such standardization and was therefore abandoned. It would be interesting, however, to study the effect of various pressures on the viscosity of flour-in-water mixtures as shown by a capillary viscosimeter, as the rate of shear was found to have a marked effect on the results obtained. A study of this factor might throw some light on the problem.

The ease of manipulation and the speed with which determinations could be carried out, together with the comparative accuracy with which duplicate determinations could be made, as shown in Table IV, led to the use of a MacMichael viscosimeter for the main part of this work. Because of mechanical construction of the viscosimeter and the effect of different rates of shear on the viscosity readings, the results obtained are only comparative. As the instrument was so constructed that the different parts of the liquid were subjected to different rates of shear, no study of the effect of rate of shear on viscosity of the flour-in-water suspensions would be valid. The results are all expressed in terms of degrees MacMichael because the attempt at expressing them in terms of absolute viscosity would only be misleading, and for that reason no attempt was made to standardize the wire used except to give an approximate idea of the magnitude of the readings in absolute units.

Some might question the value of such extended determinations on the same flours because flours are known to change markedly in baking strength with age. The investigations on these flours were not begun until about six months after the flours had been milled. They were baked at intervals extending over a year. The flour was stored in sealed containers in a cold storage plant at a temperature of about 3° C. The imbibitional powers of the hand-washed crude gluten obtained from flours B-780 and B-783, as measured by increase in weight of discs in the presence of various concentrations of lactic acid, did not change after being kept in storage for two years. The determination was carried out at the beginning and the end of the work with flours B-780 and B-783. For these reasons it is believed that no significant error due to changes in the flour during the progress of these experiments was introduced. It was believed that the investigation would yield more profitable results if a few flours were studied from as many angles as possible rather than fresh flours for each point investigated.

VISCOSITY OF ORIGINAL FLOUR-IN-WATER SUSPENSIONS AS AFFECTED BY VARIOUS AMOUNTS OF DIFFERENT ACIDS

In this investigation the viscosity as affected by a series of normal acids was studied to see if the various acids behaved alike with the different flours. For this study flours B-780 and B-783 were used, the same that were used in the earlier study by Sharp and Gortner (1922).

Table II shows that the increase in viscosity of flour B-780 begins with smaller additions of acid than with B-783. This same effect was observed with all the acids studied in Table III but it was considered sufficient to give only a few examples. As a partial explanation of this difference between the two flours, it should be noted that flour B-780 had an ash content of 0.44 per cent and flour B-783 an ash content of 0.53 per cent. In view of the work of Bailey and Peterson (1921) it would be expected that the addition of the same amount of acid to the two flours would cause a greater change in hydrogen-ion concentration in flour B-780 than in flour B-783. The results presented in Table III show that this is indeed the case.

The results obtained with the various acids are expressed graphically, using in the first instance the cubic centimeters of normal acid added as abscissa (see Figs. 1 and 2) and in the second instance the pH of the various acid solutions as abscissa (see Figs. 3 and 4). The viscosity in degrees MacMichael is used as ordinates in each case. The results are plotted on the different bases in order to show how easy it is to overlook a really fundamental similarity in the behavior of the various acids.

Figures 3 and 4 show clearly that the greatest imbibitional effect which a given acid will produce occurs at practically the same hydrogen-ion concentration regardless of the nature of the acid. This hydrogen-ion concentration appears to be approximately at pH 3.0 for the flour proteins and to be the same within experimental error for the two flours.

That the two flours seem to respond differently to different rates of shear, is shown by a comparison of the values obtained with lactic acid as shown in Tables III and V when different wires were used in the viscosimeter.

If the points of maximum viscosity produced by the various acids with the two flours are compared, it will be noticed that the order of the acids is different in the two flours. Sulfuric acid produces only slight imbibition in the case of flour B-780 and no imbibition in the case of flour B-783. Trichlor acetic acid produces appreciable imbibition with flour B-780 and practically no imbibition with flour B-783.

Meta-phosphoric acid produces no imbibition with either flour. This failure to cause the imbibition of the proteins of the flour is undoubtedly connected with the behavior of these acids as protein precipitants. The experiments with flour proteins would indicate that meta-phosphoric acid would be the most efficient protein precipitant of the acids studied.

EFFECT OF ADDED SALTS ON IMBIBITION PRODUCED BY LACTIC ACID

In these experiments the water with which the flour was treated was made 0.01 normal with respect to several salts and the effect of lactic acid on imbibition was measured by the viscosity method. In the case of dibasic potassium phosphate the concentration used was 0.005 molar. The results are given in Tables VI and VII and are expressed graphically in Figure 5. It was found that magnesium, potassium, and sodium chlorides, and dibasic potassium phosphate all produced about the same decrease in viscosity, both flours behaving similarly in this respect. Magnesium sulfate, potassium sulfate, and calcium chloride were found to decrease the viscosity still more, all three salts decreasing it to about the same extent. The two flours behaved alike in this regard. In the case of the last three salts the beginning of the increase in viscosity is delayed. This is also true with the dibasic potassium phosphate. The effects of these salts fall in very sharply defined groups. The groups are not determined by the valency of the ions, for magnesium chloride falls in the upper group while calcium chloride falls in the lower one. Dibasic potassium phosphate falls in the upper group and magnesium sulfate and potassium sulfate fall in the lower group in spite of the fact that dibasic potassium phosphate is present in slightly greater amount. Potassium and sodium chloride both fall in the same group, the results agreeing with each other within experimental error.

EFFECT OF ELECTROLYTES PRESENT IN THE ORIGINAL FLOUR ON VISCOSITY

It is known that the water extract from wheat flour contains a certain amount of dissolved electrolytes, and it would be expected that they would exert some effect in decreasing the viscosity of the flour-in-water mixture. It has been shown by Bailey and Collatz (1921) that the soluble electrolyte content of a water extract of wheat flour, as measured by conductivity, was related to the ash content of the flour, so the viscosity of a low-grade flour should be depressed more than that of a high-grade flour, owing to the difference in soluble electrolytes contributed to the extract by the flour itself. Thus the true imbibitional strength of the proteins present would be somewhat masked by the ash content, and flours of different grades contributing different amounts of salts should not be expected to respond alike.

In order to investigate this point, two flours of widely different ash content were chosen. It was found that extracting 18 grams of the flour with one liter of water and centrifuging and discarding the supernatant liquid and then making the residue up to a total volume of 100 cc., increased the viscosity of a flour with a high ash content from 75 to 329 degrees MacMichael, while a flour with a relatively lower ash content increased from 393 to 502 degrees. This confirmed the supposition that the difference in soluble salts of the different flours was changing the order of their relative viscosities. A second extraction with one liter of water was not found to affect the viscosity appreciably. This treatment with one liter of water was found to reduce the salt content as shown by conductivity determinations, to at least one-fifteenth its original value. The subsequent extraction with one liter of water was found to reduce the content slightly further. It was thought, therefore, that this treatment lowered the electrolyte content to a level where it would not affect the results.

EFFECT OF VARIOUS ACIDS ON VISCOSITY OF EXTRACTED FLOURS

In view of the demonstrated effect of the soluble salts, the viscosity determinations were repeated with the various acids on the same flours, B-780 and B-783, after they had been extracted with one liter of water. The results are given in Table IX and Figures 6 and 7. The effect of removing the soluble salts seemed to be to increase the viscosity of B-783 more than that of B-780 and this is just what was expected from the ash content. The acids seemed to behave more nearly alike with the two different flours after the removal of the soluble materials. In order to bring out more clearly the effect of removing the soluble materials, the acids are grouped in Table XXV in order of their power to increase the viscosity of the flour suspension. The table gives the order with flours B-780 and B-783 both with and without the soluble materials. In order to show how the effects of the different acids on the two flours become more nearly alike after the removal of the extract, the maximum points obtained with the various acids are grouped together in Table XXVI, which also gives the ratios of the maximum viscosities as a means of comparison of the two flours. It is seen that in the extracted flours the ratio is more or less constant, while in the unextracted flour it varies considerably. The optimum pH for imbibition in the extracted flours seemed to be slightly on the

TABLE XXV

ION SERIES AT MAXIMUM VISCOSITY FOR FLOURS B-780 AND B-783, AS SHOWN BY VISCOSITY DETERMINATIONS WITH VARIOUS ACIDS, WITH AND WITHOUT REMOVAL OF WATER-SOLUBLE EXTRACT

Columns begin with the acid showing greatest increase in viscosity. Acids producing approximately the same increase are placed in groups.

Soluble extract present		Soluble extract removed	
B-780	B-783	B-780	B-783
Oxalic	H_3PO_4	H_3PO_4	H_3PO_4
Tartaric			
H_3PO_4	H_3PO_3	HCl	HCl
H_3PO_3	Lactic	HBr	H_3PO_3
		HNO_3	
$CH_2ClCOOH$	HCl		HNO_3
Lactic		$CH_2ClCOOH$	Lactic
	$CH_2ClCOOH$	H_3PO_3	$CH_2ClCOOH$
HCl		CH_3COOH	
	Tartaric		Citric
Citric	Oxalic	Citric	Oxalic
		Lactic	Tartaric
CH_3COOH	CH_3COOH	$CHCl_2COOH$	
	Citric		CH_3COOH
HNO_3		Oxalic	
	HNO_3	Tartaric	H_2SO_4
CCl_3COOH			
	CCl_3COOH	CCl_3COOH	
H_2SO_4			
	H_2SO_4	H_2SO_4	
HPO_3			
	HPO_3	HPO_3	

TABLE XXVI

MAXIMUM VISCOSITY, IN DEGREES MACMICHAEL, PRODUCED WITH VARIOUS ACIDS AND ALKALIES USING FLOURS B-780 AND B-783 BOTH WITH AND WITHOUT REMOVAL OF SOLUBLE EXTRACT

The ratio of the maximum viscosity produced with the same acid on the two different flours is also shown.

Acid	Viscosity salts present			Viscosity salts removed		
	B-780 M°	B-783 M°	$\frac{\text{B-780}}{\text{B-783}}$ ratio	B-780 M°	B-783 M°	$\frac{\text{B-780}}{\text{B-783}}$ ratio
Hydrochloric	273	128	2.14	389	258	1.51
Lactic	280	140	2.00	322	234	1.38
Tartaric	332	118	2.81	305	211	1.45
Oxalic	337	113	2.98	310	211	1.47
Sulfuric	98	33	2.97	111	81	1.37
Acetic	216	105	2.06	333	203	1.64
Nitric	195	66	2.96	373	234	1.59
Citric	247	103	2.40	322	213	1.51
H_3PO_4	332	163	2.04	401	267	1.54
H_3PO_3	332	160	2.08	339	240	1.41
$CH_2ClCOOH$	311	130	2.39	340	230	1.48
CCl_3COOH	147	41	3.58	...	...	...
NaOH	625	342	1.83	387	194	1.99
$Ba(OH)_2$	185	140	1.32	73	43	1.70

alkaline side of pH 3.0. While in many ways the behavior of the different acids appears to be similar, the curves show differences which are still much greater than the experimental errors of the method. It is noted that the freshly prepared meta-phosphoric acid produces no imbibition. This indicates its efficiency as a protein precipitant. The change of meta-phosphoric acid to ortho-phosphoric acid is shown by the effect produced by the acid solution that stood for several months.

EFFECT OF SODIUM AND BARIUM HYDROXIDE ON VISCOSITY OF FLOUR SUSPENSIONS

Barium hydroxide has relatively less effect on the viscosity of the flour suspensions than has sodium hydroxide. This agrees with the findings of Loeb (1921a) and Zoller (1921) for other proteins. Lüers (1919) found that barium and sodium hydroxide increased the viscosity of gliadin solution to practically the same extent. The salts present in the flour repress imbibition in alkalies only to a slight extent, but they exert a marked depressing effect on imbibition in acids, as shown in Figures 8 and 9. The point of maximum viscosity is reached with the two flours at a pH of approximately 11.0, using sodium hydroxide, and at a pH a little higher using barium hydroxide. It was noticed that if the flour in the alkali was kept at its highest point of imbibition for some time, the viscosity decreased with time without the addition of further amounts of alkali. The results obtained with hydrochloric and sulfuric acids are plotted in the same figures to show the effect of a wide range of pH.

The effect of lactic acid on the viscosity of a series of flours was studied in order to see whether or not the viscosity values could be correlated with the baking data. The results showing the maximum viscosity with the extract both present and removed are given in Table XII. Several correlations were made, indicating what appeared to be a relation between the loaf volume, the protein content, and the viscosity values with the extract removed. There were several exceptions, however, indicating that some other factor which had not been taken into account was affecting the results.

EFFECT OF CONCENTRATION ON VISCOSITY

This point was investigated to see whether or not the order of the relative viscosities of the various flours would remain the same if the viscosity effects were measured at different concentrations. The results (Tables XIII and XV) show that concentration does affect the results. It is shown that the effect of concentration on viscosity can be expressed by the equation

$$\log. \text{ viscosity} = a + b \log. \text{ concentration}$$

It was found that the constant *b*, which is the tangent of the angle made by the logarithmic curve with the axis of abscissa, varied with the different flours. Apparently the value of the constant *b* expressed more nearly the imbibitional strength of the various flours. The values for the constant *a* were found to vary markedly when the concentration was calculated on the basis of grams of flour per 100 cc. If the concentration of the protein content was used the values for *a* more nearly approach each other, while if the concentration was expressed as glutenin the values for *a* show still greater agreement. The values obtained for these constants are given in Tables XIV and XVI. The values for the constants of the curve were determined by the method of least squares. The value of *b* was also obtained by the graphical method.

PROTEIN FRACTIONS IN VARIOUS FLOURS

Gliadin is reputed to have but a slight solubility in distilled water. However, the amount of gliadin removed by water during the extraction of the electrolytes was determined and found to be very appreciable. The results, shown in Table XIX, indicate that it is the alcohol-soluble protein which is removed, for the total amount of protein removed by the water and the subsequent alcohol treatment is only slightly greater than the amount of protein removed by direct treatment with alcohol, i.e., 9.33 and 9.04 per cent, respectively. That it is the alcohol-soluble protein which is removed is indicated by the difference in amounts of protein removed from the 18- and 9-gram samples. More protein was removed by the water treatment and less with the alcohol treatment from the 9-gram sample than from the 18-gram sample.

The results given in Table XX seem to indicate that most of the alcohol-soluble protein can be removed by extraction with water, and that the greatest amount is removed in the first four extractions. In this case the treatment with water and alcohol removed more than 10 per cent of protein, probably including some glutenin. This is highly probable as the material was extracted with water by decantation and some of the glutenin particles might easily have remained in suspension and have been carried over with the decanted liquid, as it was not filtered.

Other observations during the progress of the work indicated that the glutenin is mainly responsible for the imbibitional powers of the proteins of the flour and gluten. This supposition was confirmed by the viscosity determination on the flour from which the gliadin had been extracted. This material always showed a viscosity of the same order of magnitude as the original flour. The viscosity readings were always considerably lower in the flour from which the gliadin had been extracted by treatment with water followed by alcohol than in material that had not been treated with alcohol. This last treatment with alcohol removed only the small part of the alcohol-soluble protein which had not been removed by water. Thus alcohol shows a marked effect on the viscosity, either by the removal of this last small amount of alcohol-soluble protein or, which seems more probable, by the denaturization of the glutenin, it being well known that alcohol coagulates certain proteins. This latter explanation would be more in agreement with the findings of Sharp and Gortner (1922), who dried crude gluten at a temperature below 50° C. and found that the colloidal properties of the material were markedly altered.

The effect of lactic acid on the viscosity of flour-water suspensions which had been extracted several times with 500 cc. of distilled water was enormous (Table XXI and Fig. 12). The addition of only 0.10 cc. of normal lactic acid was sufficient to increase the viscosity over ninety times its original value. This material, which had reached its maximum point of imbibition by treatment with lactic acid, was very sensitive to the addition of salts, the value decreasing nearly two-thirds on the addition of 0.10 cc. of magnesium sulfate. Magnesium chloride was not so effective in this respect. Another interesting point is that the viscosity obtained was much greater than when the extraction was made with only one liter of water, which gave a value of 258° M., thus indicating that the effect of the electrolytes of the flour had probably not been entirely eliminated by a single extraction with one liter of water.

Because these experiments seem to show that the glutenin is mainly responsible for the imbibitional powers of the flour, the attempt was made to determine the relative amounts of the various proteins in the flours investigated. It was found that centrifuging the 5 per cent potassium sulfate-soluble extract before filtration apparently increased the amount of protein removed in this fraction. It was found that the direct treatment with 70 per cent alcohol removed about the same amount of protein as extracting first with 5 per cent potassium sulfate and then with 70 per cent alcohol.. It was believed that the glutenin content would be indicated more accurately by subtracting from the total crude protein the sum of the protein extracted with potassium sulfate and that extracted subsequently with 70 per cent alcohol.

TABLE XXVII

Relation Between Loaf Volume, Glutenin Content, and the Imbibitional Strength of the Glutenin as Represented by the Constant *b* of the Logarithmic Equation

Lab. No.	Loaf volume	Glutenin content	Electrolytes present		Electrolytes removed		Class of wheat	Flour grade
			Constant *b*	$\frac{(\text{Glutenin}) \times (b)}{(\text{Loaf volume})} = K$	Constant *b*	$\frac{(\text{Glutenin}) \times (b)}{(\text{Loaf volume})} = K$		
1009	2160	6.92	3.291	0.01054	2.622	0.00840	Hard Red Spring	Patent
1001*	2010	5.70	3.705	0.01051	3.023	0.00857	Hard Red Winter	Patent
1008	2000	7.45	2.643	0.00985	2.212	0.00824	Hard Red Spring	Patent
1005†	1820	5.45	2.766	0.00828	2.666	0.00795	Hard Red Spring	Patent
1010	1760	5.05	3.005	0.00862	2.909	0.00834	Kofod	Straight
1006‡	1735	5.48	2.996	0.00946	2.610	0.00823	Hard Red Spring	Patent
1011	1720	4.93	2.797	0.00801	2.398	0.00687	Soft Red Winter	Patent
1003	1650	4.19	3.013	0.00765	2.499	0.00635	White Club	Straight
1002*	1880	6.55	2.689	0.00936	2.926	0.01060	Hard Red Winter	First clear
1007‡	1460	6.47	3.052	0.01352	2.568	0.01137	Hard Red Spring	First clear
1004†	1415	6.11	2.829	0.01221	2.552	0.01071	Hard Red Spring	Second clear

* 1001 is a patent and 1002 a clear from the same wheat.

† 1005 is a patent and 1004 a clear from the same wheat.

‡ 1006 is a patent and 1007 a clear from the same wheat.

RELATION OF VISCOSITY, GLUTENIN CONTENT, AND LOAF VOLUME

It has been shown in Figures 10 and 11 that the logarithmic curves do not all lie at the same angle with respect to the axis of abscissa, that is, the viscosity increases more rapidly with concentration in some cases than in others. It is probable that the tangent of the angle of this curve made with the abscissa represents more accurately than any other value thus far obtained, the imbibitional strength of the colloidal protein of the wheat. If the tangent of this angle is small, the colloidal properties will be less marked; on the other hand, if the tangent of the angle has a large value, the colloidal properties will be very pronounced. The constant b in the equation

$$\text{log. viscosity} = a + b \text{ (log. concentration)}$$

represents the tangent of this angle.

Bearing in mind that the tangent b of the angle thus obtained might be considered as the value indicating most accurately the colloidal strength of the flour, and that the imbibition of flour as affected by acids is due mainly to the glutenin, it should be expected that a relationship might exist between these two factors. Thus the colloidal strength of the flour would be the product of the quality factor as indicated by the constant b in the logarithmic equation, and the quantity factor as indicated by the quantity of glutenin present in the flour. In order to see if this product was actually related to the baking strength of the flour as indicated by loaf volume, the former was divided by the latter. The results of this calculation are given in Table XXVII.

Suspensions of various concentrations of flour untreated with acids would doubtless follow the logarithmic relationship and would probably give an angle somewhat similar to the ones obtained in Figures 10 and 11. Unfortunately, the supply of flours used became exhausted, so it was impossible to compare the curves produced with the untreated flours with those given in Figures 10 and 11. The attempt was made to introduce the relationship between the initial viscosity reading of the flour-in-water suspension and the maximum reading after treatment with lactic acid, but the initial reading was so low that it could be determined only approximately with the viscosimeter set for the higher readings, the experimental error being in some cases about 50 per cent. It would seem desirable to investigate this point under conditions in which the lower readings could be determined with sufficient accuracy to subject this relationship to a more exact quantitative study. Likewise the subtraction of the initial value from the maximum value was tried but in some cases this produced relatively large values for the constant b, because some of the flours with low baking strength yielded simple flour-in-water suspensions which gave relatively high readings; and altho these suspensions increased only slightly in viscosity on the addition of acids, subtracting the initial value from the final value and plotting this difference gave relatively large values for the constant *b*.

The values for the constant *b* are higher for the series with the electrolytes present than for the series with the electrolytes removed. The wires used in the two series both gave a reading of 29.2° M. with a 60 per cent sucrose solution whose absolute viscosity is 43.86 centipoise at 25° C., the temperature at which all observations were made. Unfortunately, the wire of the viscosimeter broke after one series had been completed and a new wire was used for the other series. The breaking of the wire was a great misfortune, because it leaves the question of the effect of the salts present in the original flour, on the slope of the curve, still unanswered. The results do show, however, that the salts present in the flour exert an effect which differs in different flours, indicating that the electrolytes present in the various flours are different. This is also shown in Figures 3 and 4 and may be the explanation for the different order of the acids when arranged in the order of their power to produce maximum imbibition. The order of the acids was found to be more nearly the same when the electrolytes were removed. See Figures 6 and 7. The effect of the actual quantity of supposedly the same electrolytes from the same wheat is shown in a comparison of the patent and clear flours from the same wheat in Table XXVIII.

TABLE XXVIII

Relation Between Patent and Clear Flours Milled from the Same Wheat and the Constant *b* of the Logarithmic Equation

Lab. No.	Constant *b*, electrolytes present	Constant *b*, electrolytes removed	Flour grade
1001	3.705	3.023	Patent
1002	2.689	2.926	First clear
1005	2.766	2.666	Patent
1004	2.829	2.552	Second clear
1006	2.996	2.610	Patent
1007	2.829	2.568	First clear

The greatest deviation between the constants *b* is shown when the electrolytes were present. Patent flour 1001 gave a constant of 3.705 and clear flour from the same wheat, 1002, gave a constant of 2.689. In the other two cases the agreement is better. When the electrolytes were removed, the patent flour in each case gave a slightly higher constant than the clear flour, indicating that the protein in the patent flour was of only slightly better quality than the protein in the clear flour. This agreement is also an indication that the influence of the electrolytes present in the flour was largely eliminated, so far as their effect on the evaluation of the imbibitional properties of the gluten was concerned, by the method of leaching used for their removal.

The constant K, obtained by dividing the product of the glutenin concentration and the constant *b*, by the loaf volume, shows considerable fluctuation in the series with the electrolytes present. When the electrolytes are removed we find the constants apparently fall into three groups. With the exception of flour 1010, the first group contains patent or straight flours which would be used for bread making; the second group contains flours which if used by themselves would be considered pastry flours and would be used commercially for bread making only when blended with other flours of considerable baking strength; the third group contains the clear flours. The average of the constants K in the first group is 0.00829, the average deviation from this value is 1.99 per cent, and the maximum deviation is 4.1 per cent. The average in the second group is 0.00661, while the average and maximum deviation is 3.93 per cent. The average in the third group is 0.01089, the average deviation is 2.91 per cent, and the maximum deviation is 4.41 per cent. The greatest experimental error is believed to be in the determination of the glutenin content of the flours. These results indicate a rather definite relation between the glutenin content, the increased concentration effect of imbibition produced by lactic acid, and the loaf volume. It is generally accepted that the actual volume of the loaf obtained depends on many factors, and it could hardly be expected that the measurement of one factor would determine the loaf volume. These results indicate that within each group there is a definite relation between the glutenin content, the quality content *b*, and the loaf volume. The groups of different constants are probably produced by other factors. Just what these other factors are has not been determined, other than the relation expressed in Table XXVII between the class and grade of wheat and the grade of flour. Some correlations which might be drawn from the work carried out by Rumsey (1922) and Collatz (1922) using these same flours might be mentioned here, more in the way of discussion than of definite conclusions. Collatz found that by the addition of malt flour or extracts the loaf volume of flours 1002 and 1007 could be increased about 16 per cent. Increasing the loaf volumes used for these flours in Table XXVII by 16 per cent we obtain the constant 0.00833 for flour 1002 and 0.00922 for flour 1007. The volume of flour 1001 was increased 10 per cent, which gives a constant of 0.00779 instead of 0.00857. Flour 1008 showed no increase in volume on the addition of malt flour or extract. Flour 1003 showed an increase of 12 per cent which changes the constant to 0.00566. It is undoubtedly unfair to take the increase of this flour as 12 per cent, for this great increase occurred with only one loaf and was apparently too high. Rumsey (1922) has shown that flour 1004 has about the same diastatic power as flours 1002 and 1007. It is probable that an increase in volume might have been obtained with this flour by the addition of diastase. Table XXIX gives the relative diastatic powers of the flours as determined by Rumsey. The hydrogen-ion concentration of the flour and the fermented dough at the time of going into the oven are taken from the paper by Collatz (1922).

TABLE XXIX

Maltose Produced in One Hour by 10 Grams of Flour in 100 cc. of Water at 27°C.; the pH Value of a 1 to 5 Flour-in-Water Suspension, and of the Fermented Dough at Time of Going Into the Oven

Lab. No.	Maltose produced, mgms.*	Flour, pH†	Fermented dough, pH†
1009	211.8	....	....
1001	248.2	5.81	4.79
1008	304.1	5.98	5.19(?)
1005	131.9	5.84	5.17
1010	92.6	....	....
1006	105.7	5.78	5.03
1011	51.7	6.15	4.92
1003	34.8	6.00	5.05
1002	186.5	6.05	5.05
1007	123.6	6.10	5.53
1004	145.0	6.17	5.80

* Determinations by Rumsey (1922).

† Determinations by Collatz (1922).

Table XXIX shows that only two flours, namely, the clear flours 1004 and 1007, did not reach approximately a pH of 5.0, which the work of Jessen-Hansen (1911) indicates to be the general optimum for bread making. Thus, one reason for the low volumes of these two flours may have been that the optimum hydrogen-ion concentration had not been reached. The clear flour 1002 did reach this optimum, and making the correction for the increased volume produced by added diastase yields a constant which agrees with those in Group 1. This indicates that the factor causing the low volume was insufficient diastase and not the buffer effect due to grade. Flour 1007 was improved by added diastase, yet it still gives a constant which is too high for Group 1. It may be that the low loaf volume in this case is caused by two factors, namely, the low diastase content and the failure of the dough to reach the optimum hydrogen-ion concentration for bread baking, owing to its high buffer action.

If we take the first group of flours for comparison, then the second group yields larger loaf volumes than their glutenin content and its imbibitional properties would indicate. No hypothesis will be expressed as to the factors operative in the formation of Group 2. The flours in Group 2 are especially low in diastase. An increase in diastatic power would have a tendency to increase the loaf volume and yield a still lower constant.

While eleven flours with such meager data are far too few upon which to base definite conclusions, this work indicates that the glutenin content and its imbibitional properties may be used as a measure of one of the main factors concerned with baking strength. While the data presented here indicate three groups of flours as shown by the imbibitional studies, later work may show more than three groups. In the method used, all the factors which go to make up viscosity and plasticity were probably operative.

Gröh and Friedl (1914) found that the gliadins in wheat and rye flour were identical in physical properties. Lüers and Ostwald (1919) found that the viscosity of wheat flour suspensions was increased by the addition of lactic acid, while the viscosity of rye flour suspensions remained unaffected. The experiments reported here indicate that the colloidal properties of glutenin, as shown by its imbibitional power as affected by acids and alkalies, constitute one of the factors concerned in strength of flour. A comparison of the results reported here with those of Lüers and Ostwald would indicate that the glutenin of rye flour is markedly different from the glutenin of wheat flour; and from the results of the studies on the viscosity of wheat gluten reported here, it would be expected that rye flour would behave as an extremely weak flour.

Guthrie (1896) seems to be the first investigator who definitely attributes the strength of flour to the glutenin. Since the experiments reported in the present paper were completed, Woodman (1922) has reached the conclusion that the glutenin fraction is concerned in the problem of flour strength. Woodman extracted the proteins, gliadin and glutenin, from samples of strong (Canadian) and weak (English) flours and then followed the changes in optical rotation of these pure proteins when they were racemized with dilute alkali at 37°. He concludes that the gliadin fractions of both strong and weak flours are identical in physico-chemical behavior but that there is a marked difference in the glutenins. He states, "The glutenines from the two types of flour have been shown to be two distinct substances, this conclusion being based on their different optical behavior during racemization by dilute alkali.

"It is suggested that the existing ideas on flour strength require modification to include the facts recorded in this investigation. It is desirable to retain the dual conception of strength as put forward by Wood. The factor which determines the size of the loaf is most probably connected with the diastatic capacity of the flour, as was suggested by this investigator. On the other hand, the factor which determines the shape of the loaf and which appears to be directly related to the physical properties of the gluten of the flour, is possibly dependent on the particular glutenine mechanism possessed by the wheat.

"The results of this investigation suggest that the strong wheat synthesizes one type of glutenine and the weak wheat a different type, whilst wheats of intermediate strength may contain varying proportions of the two glutenines."

It will be noted that these conclusions are very similar to our own, reached from an entirely different sort of evidence, and we regard Woodman's work as strongly confirming the hypothesis that flour quality is intimately associated with the glutenin fraction of the wheat proteins.

While the present investigation indicates that the amount and colloidal properties of the glutenin are important factors concerned with flour strength, more extensive investigations must be carried out before final conclusions can be drawn.

NATURE OF VISCOSITY CHANGES INDUCED BY ADDITION OF ACIDS AND ALKALIES

The viscosity curves shown in Figures 3, 4, 6, 7, 8, and 9 of the present paper are very similar in appearance to those which Loeb (1920a, 1920b, 1920c, 1921a, 1921b, 1921c, 1921d, 1921e, 1921f, and 1922) presents for gelatin, casein, etc. Loeb interprets his results as being due to stoichiometrical combination of the protein with the acids or bases followed by ionization of the protein salt and hydration of the protein-ion by osmotic phenomena governed by the Donnan (1911) equilibrium. In other words, Loeb apparently takes the view that imbibition changes in a protein system are due to chemical reactions, whereas the prevalent viewpoint of workers in the field of colloids is that they are due to surface phenomena. Certain of the experiments which we have reported appear to throw light upon these questions.

The experiments reported in Tables XIX and XX show that gliadin is relatively soluble in distilled water and that the gliadin can be almost completely removed from wheat flour by leaching with water. It will be noted from Table XV that 18 grams of flour 1009, from which the soluble salts had been removed by leaching with one liter of water followed by 500 cc. of water, attained a maximum viscosity of 258° M. when treated with lactic acid.

As shown in Table XIX, the same treatment followed by four extractions with alcohol gave viscosity readings of 191° M. and 195°M.; and (Table XX) sixteen extractions with 500 cc. distilled water followed by an extraction with alcohol gave a viscosity reading of 149° M.

It might be argued from the above experiments that the alcohol removed some of the protein, which was responsible for the increase in viscosity produced by the addition of lactic acid. That this is not the case, however, is shown by Table XXI and Figure 12. In this instance 18 grams of the same flour was leached with from 8 to 16 successive portions of 500 cc. each of distilled water, *but the alcohol extraction was omitted* and a maximum viscosity of 456° M. was attained. Apparently the alcohol treatment was responsible for the lower viscosities shown in Tables XIX and XX.

This enormous increase in viscosity from 4° M. to 456° M. was produced by the addition of 0.4 cc. of a normal solution of lactic acid, and an increase in viscosity from 4° M. to 365° M. was caused by even 0.10 cc. of normal lactic acid.

According to Loeb's hypothesis, in order that viscosity changes may take place, there must first be a chemical combination of the acid with the protein, followed by the ionization of the protein salt and the subsequent hydration of the protein ion through osmotic behavior controlled by the Donnan equilibrium. It appears very improbable that equilibrium would be reached practically instantaneously if osmotic phenomena are involved; nevertheless, equilibrium was reached practically instantaneously (within 2 or 3 seconds) in our experiments. On the addition of 0.1 cc. of normal magnesium sulfate solution to such a system, the viscosity fell practically instantaneously to a small fraction of its former value. Here again the rapidity of the changes is not suggestive of osmotic behavior. It appears far more probable that the reactions involved are due to surface phenomena, and the viscosity changes on the addition of acid and salt may be likened to the changes which take place when an electric current is passed through an electro-magnet suspended above a pile of iron filings and the current is later broken by throwing the switch. Apparently on the addition of the lactic acid a comparatively thick "shell" of water is bound upon the surface of the glutenin particle, only to be instantly released when the salt is added. If the water penetrated into the interior of the glutenin particle by osmosis, there should be a gradual fall in viscosity when dehydration takes place. It has been impossible to demonstrate such a slow fall, equilibrium being attained practically instantaneously.

Again, if the view is correct that hydration of proteins is a phenomenon controlled only by the hydrogen-ion concentration, it is impossible to understand why glutenin shows such marked imbibition changes in contrast to the behavior of the prolamine, gliadin, or why glutenin from a strong flour shows such marked differences in behavior from glutenin from a weak flour *at the same hydrogen-ion concentration and salt content.* In our experiments, hydrogen-ion concentration does markedly influence imbibition; nevertheless, the fact remains that "there is an inherent difference in the glutens from strong and weak flours. The physico-chemical properties of the glutens from the different flours are not identical and would not be identical even if the flour had originally had the same acid (hydrogen-ion concentration) and salt content. The difference between a strong and a weak gluten is apparently that between a nearly perfect colloidal gel with highly pronounced physico-chemical properties, such as pertain to emulsoids, and that of a colloidal gel in which these properties are much less marked." These statements were made by Gortner and Doherty in 1918, and our present work seems to emphasize their findings. We have advanced the knowledge of the flour strength problem so as to limit, apparently, the difference of colloidal behavior to the glutenin fraction of the flour proteins, but the difference in the glutenin is apparently due to its behavior as emulsoid colloids. This is particularly apparent in the baking tests (Table XXIV, Plates 1 and 2) in which an alteration in the colloidal properties of the glutenin ruined the baking value of the flour. Other experiments which are now in progress point to the same conclusions.

SUMMARY AND CONCLUSIONS

Viscosity of flour-in-water suspensions was used as an easy, rapid, and accurate method for the investigation of the comparative imbibitional properties of the flour proteins. Viscosity studies were made on a series of wheat flours of various grades and baking strength in an effort to investigate the relation of the colloidal properties of wheat proteins to the strength of flour.

Suspensions of flour in water are extremely labile systems and are affected by the many factors which influence the viscosity of emulsoid colloids.

Maximum viscosity produced by the various acids acting on wheat flours occurs at approximately the same hydrogen-ion concentration regardless of the acid. The hydrogen-ion concentration for maximum viscosity was found to be slightly higher than a pH of 3. The highest viscosity produced by the different acids occurs at practically the same hydrogen-ion concentration with the different flours.

Different acids apparently do not produce the same maximum imbibitional effect with wheat proteins.

Materials extracted from flour by water influence the imbibitional power of the various acids in different degrees. The water extract from various flours differs in its effect on imbibition produced by different acids. The series of acids arranged in the order of their ability to produce maximum viscosity is more nearly the same for the different flours after the removal of the soluble extract.

Salts added to the flour-in-water suspension apparently divide themselves into sharply defined groups in respect to their ability to inhibit imbibition produced by lactic acid. These groups were found to be the same with the two flours investigated.

Failure of some acids to produce imbibition is probably related to their effect as protein precipitants.

Viscosity in the presence of alkalies is not so markedly affected by the soluble materials present in the natural flour as in the presence of acids. The maximum viscosity produced by alkalies occurs at approximately a pH of 11.

Maximum viscosity and concentration of flour were found to conform to the logarithmic expression,

$$\text{Log. of viscosity} \doteq a + b \ (\text{log. of concentration})$$

in which the log. of viscosity is the logarithm of the maximum viscosity obtained with lactic acid.

Repeated extraction of flour with distilled water removes practically all the alcohol-soluble proteins. The first extraction with water removes proportionately more than the subsequent extractions.

Glutenin is the protein mainly responsible for the marked imbibitional power of flour and gluten as influenced by acids and alkalies. The treatment of glutenin of flour with alcohol of a concentration of 70 per cent or more, markedly affects the colloidal properties of the glutenin as measured by viscosity. The imbibitional strength of the glutenin is probably represented most accurately by the constant b of the logarithmic expression noted above.

These results seem to indicate that the glutenin content and its imbibitional properties should be taken into account in investigations of flour strength.

Doughs which have been brought to a pH of 3.0 or 11.0 by the addition of acid or alkali and then the acid or alkali neutralized, have lost their baking strength.

Flours that contain a protein which responds markedly to the increasing imbibitional effect of lactic acid lose their baking strength if they are doughed up with 70 per cent or 95 per cent alcohol and then dried. The fact that the baking strength of flour is lost by extraction of the flour with alcohol is not proof that the gliadin is the protein mainly concerned with flour strength.

The viscosity determinations indicate that the effect of the alcohol is due mainly to changes produced in the colloidal properties of the glutenin.

The earlier conclusion of Gortner and Doherty, that there is an inherent difference in the physico-chemical properties of the gluten from strong and weak flours and that these differences are due to the colloidal state of the gluten proteins, is confirmed. In addition, it has been shown that the differences in colloidal properties apparently reside in the protein, glutenin.

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The University of Minnesota
Agricultural Experiment Station

A Study of Wilt Resistance in Flax

By H. D. Barker
Division of Plant Pathology and Botany
In Co-operation With
Division of Agronomy and Farm Management

UNIVERSITY FARM, ST. PAUL

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A STUDY OF WILT RESISTANCE IN FLAX

By H. D. Barker[1]

INTRODUCTION

Statistics of the United States Department of Agriculture[2] show that the production of oil flax in this country has steadily decreased. The average annual production from 1902 to 1911 was 23,749,000 bushels, and from 1912 to 1921 it was 13,668,000 bushels. This does not seem to be due to a lessened demand for linseed in this country. From 1902 to 1911 the average annual import was 2,375,700 bushels, with an annual average export of 2,264,400 bushels. The average export about equals the average import for the ten-year period because in the latter part of the period we changed from a flaxseed exporting nation to an importing one. From 1912 to 1920 the average annual import amounted to 12,637,800 bushels with an average export of 44,700 bushels. In Minnesota the average annual production from 1902 to 1911 was 4,911,600 bushels, while from 1912 to 1921 it was only 2,943,500. There was a similar diminution in other states. The center of flax production has steadily moved westward to new lands. For that reason flax has frequently been called a new-land crop. Notwithstanding the fact that it thrives better on new land than certain other crops and is less damaged by weeds, it may grow equally well on old lands if they are properly prepared and if wilt can be controlled.

Flax wilt is a very important factor in this decrease in flax production and in the westward migration of the crop. It is well known that when flax is grown for more than one year on the same soil the yields decrease. Because of this such soil has been termed "flax sick" soil. The disease has in reality become a limiting factor in the production of flax in certain states.

DISTRIBUTION OF THE DISEASE

Flax wilt is probably prevalent throughout the flax growing regions of the world, particularly in the seed flax areas where it is one of the most destructive diseases. Finch and Baker (11) state, "Because of the liability to disease when grown continuously on the same land, flax is grown almost universally on new lands in the United States, Canada, and Argentina. Newly turned prairie sod is very commonly sown to flax before a crop of wheat is put on the land. In the Russian fiber crop region newly cleared scrub lands are often employed and in the Netherlands the newly reclaimed 'ploder lands.' "

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[1] The writer wishes to acknowledge his indebtedness to Dr. E. C. Stakman of the section of plant pathology and to Dr. H. K. Hayes of the section of plant breeding, for their aid in defining the problems at the outset and for their supervision and kindly criticism of the work.

[2] United States Department of Agriculture Yearbooks.

SYMPTOMS OF THE DISEASE

The symptoms of flax wilt have been described in considerable detail by Bolley (1, 2). However, it may not be out of place to describe some of the more outstanding symptoms, particularly as they occur in Minnesota.

Plants may be attacked at any stage of development. In the early seedling stage they may simply "damp-off." The roots may be completely rotted. Somewhat later, when a certain amount of lignified tissue has developed in the plants, they no longer fall over but any one of many things may happen when they are attacked by the wilt fungus. If the attack is rapid and severe, complete wilting and death result. In other cases the plant may appear to be only slightly stunted or to be very unthrifty and some of the leaves may turn yellow and fall off; or the top of the plant may die and new, apparently healthy, vigorous branches may grow. Frequently only one side of the plant is affected. This is particularly true of older plants. The normal green and the dead, browned areas extend side by side up the plant and are sharply delimited from each other. In partly wilted plants the crown of the plant and the main root or underground portion of the stem may be enlarged considerably. Very late infection may find expression only in premature ripening and browning of the plants. In most of the Fusarium wilt diseases the vascular tissue of the stem near the crown of the plant is blackened or browned. This symptom often appears in flax plants that are seriously affected with the disease, altho it is by no means a universal symptom.

HISTORICAL REVIEW

The importance of disease resistance in plants, and discussions of the more important literature on the development of disease resistant varieties, have been so well and so thoroly summarized in many recent papers that only those are cited in this paper which deal particularly with flax wilt and the problems relating to the development of wilt-resistant varieties in general.

Little is known definitely regarding the early history of flax wilt. Neither is the origin of our cultivated varieties of flax well known. According to Hayes and Garber (13 p. 153) flax was grown by the Lake Dwellers of Switzerland as early as 4000 B.C. Vague descriptions in the older literature indicate that wilt may have been a serious factor in flax production for a long time. Pliny (19 p. 131), in discussing flax, remarks, "It has the property of scorching[3] the ground where it is grown and of deteriorating the quality of the very soil itself."

While the disease has undoubtedly existed in European countries for a long time, the early history of flax diseases is difficult to determine because the descriptions in the older literature are meager. The nature of the wilt disease was not known and hence different names were applied to it. It was for a long time regarded as a soil trouble. It was thought that flax extracted large amounts of food from the land, or that injurious substances were developed by it.

Broekema (9), in 1893, was among the first to separate this disease from others which had gone under the loose term "Brand." He noted the destructiveness of the disease and suspected that it was caused by a parasite. He observed resistant plants that remained healthy and vigorous in the midst of plants that had succumbed to the disease. He definitely raised the question as to whether this quality might be hereditary, and selected seeds from plants which showed no external manifestations of the disease and planted these beside seed of non-selected sorts. He decided that the plants from the selected seed developed better than the others and were much less affected with the disease; also that the susceptibility of the seedlings from such plants diminishes when compared with that of plants from non-selected seed. One of the explanations he suggested was that the descendants of resistant plants had by nature a force for greater growth and consequently greater vitality and resistance to the "Vlasbrand."[4]

Nypels (16), in 1897, called attention to the seriousness of a disease which was widespread throughout the Pays-Bas and Flanders, where it was called "Vlasbrand," and which he calls "La brulure du lin." He calls particular attention to its destructiveness and points out that on badly diseased soil it may destroy the crop. He gives Broekema credit for separating the disease from a great many others which had been termed "Vlasbrand." He also discusses a disease which he terms "l'etetement du lin" (l. c. pp. 220-21), describing the symptoms and the possible causes. From his descriptions and figures (l. c., figs. 5 and 6, p. 226), it seems quite possible that he was dealing with flax wilt.

Bolley (1, 2) demonstrated that the cause of flax wilt was *Fusarium lini* Bolley. Seed treatment and crop rotation were shown by him to be beneficial in the control of the disease. As Broekema had done earlier, Bolley (3, 5, 6) also observed that in infested fields a few plants did not succumb to the attacks of the disease when most of the plants were killed, and that a few scraggly plants survived the first year when varieties were grown on sick soil. These were selected and the progeny was somewhat resistant the following year. After several years of selection, sorts were produced which yielded well on sick soil. He states (8, p. 3), "How we obtained resistant flax plants is, in a large part, explained in previous portions of this bulletin, but no scientist has yet been able to explain just why the plants become resisant when exposed generation after generation to the action of the disease. Our experiments leave no question but that when the disease character is held constant so as to act steadily upon the roots and crop that generation after generation accumulates more resistance until there comes a time when the disease in the ground has no longer any ability to cut down the yield."

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[3] The following footnote of the translator is made: Virgil says, Georg. i 77, "Urit enim lini campum seges" – but in the sense, as Fee remarks, of exhausting, not scorching the soil.

[4] Portions of the original paper, published in the Dutch language, were translated by J. B. Osborn, a graduate student in Biochemistry.

In general Bolley concluded that two or three years' selection under disease conditions were necessary in order to isolate a resistant variety. Both individual and mass selection methods were used. At the Minnesota station, Stakman et al. (20) confirmed Bolley's remarkable results.

Tisdale (21, 22) has made very important contributions to the literature on the nature and inheritance of wilt resistance in flax. He found that resistance is only relative, owing to the profound modifying effects of environmental factors, especially temperature. At high temperatures the most resistant varieties may wilt severely, while at low temperatures susceptible varieties may escape infection. The fungus enters either susceptible or resistant plants through the stomata of the seedlings, the root hairs, and perhaps through wounds. In resistant plants, the fungus, upon entering, stimulates cork wall formation of cells adjacent to those attacked. This perhaps prevents further invasion. From experiments on hybridization, Tisdale found a marked difference in the individuality of plants of the same strain with respect to resistance in the progeny. Part of the lack of uniformity resulting from crosses between resistant and susceptible plants could be explained by varying environmental conditions. He concluded that wilt resistance is an inheritable character which is apparently determined by multiple factors.

Orton (17) developed varieties of cotton resistant to wilt, Jones and Gilman (14) varieties of cabbage resistant to yellows, and Essary (10) varieties of tomatoes resistant to wilt. Other investigators secured similar results in developing selections of plants resistant to various Fusarium wilt diseases.

Jones and Gilman (14) and Jones, Walker, and Tisdale (15) succeeded in securing varieties of cabbage resistant to *Fusarium conglutinans* Wollenw. They found that there are occasionally healthy plants even in the worst diseased fields. Selection of these gave rise to highly resistant strains. Repeated selection seemed to result in increased resistance. The degree of resistance was found to be relative. Environmental factors, especially soil temperature, influenced the development of the disease and also the disease resistance of the host. It is concluded (14 p. 34) that "It seems probable that in case the resistant strains are propagated through successive generations without repeated selection, they will tend to lose to some extent the disease resistant character."

One of the very striking peculiarities discovered by Bolley was that resistant varieties lose their resistance after they have been grown for a few years on disease-free soil. This is summarized by Hayes and Garber (13 p. 158) as follows: "Whether this behavior is a gradual decrease in resistance of the host which is roughly proportional to the length of time which the resistant variety has grown on wilt-free soil or a more or less sudden change which appears after two or three years is as yet unknown."

DEFINITION OF PROBLEM

The work of Bolley (3, 5) in securing wilt-resistant flax and of others (10, 14, 18, 20) in securing varieties of crop plants resistant to Fusarium wilts, has shown that these serious diseases can be controlled by selecting wilt-resistant types. The results in many of these cases have been similar, regardless of the differences in the crops concerned, and have indicated that resistance to wilt may be different from other types of resistance. There has been much theorizing as to the nature of this resistance and the difficulties of explaining the peculiar and striking results on the basis of the pure-line theory. It is apparent that the problem is of immense practical and fundamental importance.

In view of these facts the objects of the present investigation, which was conducted as a co-operative project between the section of plant pathology and the section of plant breeding, were:

1. To determine whether the results in selecting wilt-resistant varieties of flax could best be explained by the pure-line theory.
2. To study the effects of continued selection for wilt resistance in flax.
3. To determine whether resistance could be built up in any commercial variety of flax, or if it is a peculiar quality possessed only by certain varieties or groups of varieties.

4. To determine whether resistant varieties lose their resistance when grown on clean soil.
5. To study the relation of time of planting to the control of flax wilt.
6. To study the comparative resistance and yielding ability of the most promising selections of wilt-resistant varieties obtained at this station by previous selection.

SOURCE OF MATERIAL

The field studies were made on soil that had been continuously cropped to flax since 1914, when it was inoculated with pure cultures of *Fusarium lini*. This soil proved to be heavily infested with the pathogene in all the tests conducted on it. Several individual and bulk selections made by Stakman et al. (20) were available for further study. A short history of each of the important selections is given in Table I.

INDIVIDUAL PLANT SELECTION STUDIES

METHODS USED IN MAKING SELECTIONS

Individual plants were selected from a large number of resistant plants from the various selections, as indicated in Table I. These were labeled "R" (resistant) indicating that the plants selected were the most vigorous that could be found in several thousand of that particular selection and that such plants showed no visible symptoms of infection with *Fusarium lini*. The label "PR" indicated that the plant selected was "partly resistant"; that is, had recovered sufficiently to produce some seed. In such cases the mainfestation of wilt was variable. Frequently the central stalk had wilted and died back; or, less frequently, lateral branches were similarly affected; or in many cases one side of the stalk had been killed while the other side was sufficiently healthy to mature some seed. The selections were made when the first bolls had begun to mature.

TABLE I

INDIVIDUAL PLANT SELECTIONS MADE IN 1919

Selection	Remarks	History of parent selection
M25–1R	Normal plant	Primost, Minn. No. 25, (C. I. No. 47). Unselected for wilt resistance. The average percentage of wilt in this variety on the plant pathology plots from which the individual plant selections were made was 95.
M25–2R	Possibly slight wilt Plant slightly yellow	
M25–3R	Normal plant	
M25–4R	Normal plant	
M25–5R	Very exceptional vigor	
M25–6R	Normal plant	
M25–7PR to 13PR	Partly wilted	
25–7–1R to 25R	Normal plants	*Selection Plot IV 25-7, a wilt-resistant selection produced by bulk selection in 1914 and individual plant selection in 1915 from Primost, Minn. 25. The selection Plot IV–25–7 was subsequently named Chippewa, Minn. No. 181 (C. I. No. 178). Average percentage of wilt in 1919 was 4.
25–7–26PR to 31PR	Partly wilted	
25–7–32R to 56R	Normal plants	
175–1–1R to 25R	Normal plants	*Selection Plot III 175–1, a wilt-resistant selection produced by bulk selection in 1915 and individual plant selection in 1916, from Blue Dutch, Minn. No. 175. This selection was subsequently named Winona, Minn. No. 182 (C. I. No. 179). Average percentage of wilt in 1919 was 4.
175–1–26PR to 29PR	Partly wilted	
175–1–30R to 54R	Normal plants	
91–1–1R to 25R	Normal plants	*Plot II 91–1, a wilt-resistant selection produced by bulk selection in 1914 and 1915 and by individual plant selection in 1916, from Minn. No. 91. Average percentage of wilt in 1919 was 37.
91–1–26PR to 30PR	Partly wilted	
74–1–1R to 25R	Normal plants	Selection Plot IV 74–1, a wilt-resistant selection produced by bulk selection in 1914 and individual plant selection in 1915, from Minn. No. 74. Average percentage of wilt in 1919 was 22.
74–1–26PR to 30PR	Partly wilted	
II-09-15-1-1R to 10R	Normal plants	Selection II-09-15-1, Minn. 163, a selection for high yielding quality made from a 1909 cross between "Cantania" and "Improved." The selection II-09-15-1 had shown a certain degree of resistance in the field but was not selected for wilt resistance. Average percentage of wilt in 1919 was 91.
II-09-15-1-11PR to 25PR	Partly wilted	

* The original selections were made by the section of plant pathology.

METHODS OF SELFING SELECTIONS

Selfing was accomplished by growing the selections in the greenhouse during the winter, each plant in a separate booth formed by double walls of cheese-cloth. In this way many seeds were produced from a single plant. In a few cases selfing was done in the field by placing a cigarette tube over each flower. However, for the studies here recorded selfing was done in the greenhouse, part of the seed being saved each year for selfing in the greenhouse the following year. The rest was planted in individual rows on sick soil. A list of the parent types with a short history of each is given in Table I. This also includes outstanding features of each selection.

RESULTS OBTAINED FROM INDIVIDUAL SELECTIONS

A large number of individual plant studies were made in order to determine whether the peculiar results obtained in selecting varieties of plants resistant to wilt could be explained by the pure-line theory; to test the effect of continued selection upon the development of wilt resistance; and to determine whether resistance could be built up in any commercial selection of flax if it was continuously associated with the disease. The question naturally arose as to whether the results in obtaining wilt-resistant strains of flax could not best be explained by the pure-line theory. Other questions were: By what means does flax become resistant? What is the explanation for the widespread opinion that resistance is gradually "built up" by the association of the plant and the parasite? Why is resistance lost by the long-time removal of the plant from sick soil? Why could resistance be built up only to a certain point regardless of the method employed? Would it be possible to obtain by continuous individual plant selection and careful self-pollination, varieties that would be immune from wilt? These questions could not be answered on the basis of definite experimental proof at hand, hence it was decided to make a large number of individual plant selections and self these for several generations, if necessary, in order to be certain that homozygous selections were secured, to see what light they could throw on the problem. Accordingly, in the summer of 1919 about five hundred individual plant selections were made from the selections grown on sick soil on the plant pathology plots.

Plant selections were made as already described. A summary of these selections with a brief history of the parent type is given in Table I. These were grown in sterilized soil in the greenhouse in the winter of 1919-20. The results of the tests after one generation of selfing are given in Tables II and III.

TABLE II

REACTION OF INDIVIDUAL PLANT SELECTIONS FROM WILT-FREE PLANTS (R), IN 1919, SELFED IN GREENHOUSE DURING THE WINTER OF 1919-20, AND PLANTED ON SICK SOIL IN 1920

Selection	No. of plants	Killed by wilt		Partially wilted		Total per cent of wilt
		No.	Per cent	No.	Per cent	
M25–2R	24	3	12.5	8	33.3	45.8
M25–3R	23	4	17.4	16	69.6	87.0
M25–4R	13	1	7.7	7	54.0	61.7
M25–5R	76	7	9.2	32	42.2	51.4
M25–6R	50	21	42.0	11	22.0	64.0
Total	186	36	88.8	74	221.1	309.9
Average	37.2	7.2	17.8	15.8	44.2	62.0
25–7–2R	15	1	6.7	1	6.7	13.4
25–7–3R	10	4	40.0	2	20.0	60.0
25–7–5R	6	1	16.7	2	32.3	50.0
25–7–6R	40	8	20.0	17	42.5	62.5
25–7–7R	10	1	10.0	1	10.0	20.0
25–7–8R	15	0	0.0	4	26.8	26.8
25–7–9R	3	0	0.0	2	66.7	66.7
25–7–10R	63	13	20.3	11	17.5	37.8
25–7–11R	80	19	24.8	20	25.0	48.8
25–7–12R	29	4	13.8	4	13.8	27.6
25–7–13R	9	0	0.0	1	11.1	11.1
25–7–14R	1	0	0.0	0	0.0	0.0
25–7–16R	75	11	14.7	23	30.3	45.0
25–7–17R	80	15	18.7	24	30.0	48.7
25–7–18R	40	11	27.5	7	17.5	45.0
25–7–19R	139	39	28.1	28	20.1	48.2
25–7–20R	104	21	20.1	25	24.0	44.1
25–7–21R	107	22	20.6	36	33.6	54.2
25–7–22R	7	1	14.3	0	0.0	14.3
25–7–25R	5	0	0.0	1	20.0	20.0
25–7–32R	16	1	6.2	9	56.1	62.3
25–7–33R	71	6	8.5	32	45.1	53.6
25–7–34R	2	0	0.0	2	100.0	100.0
25–7–35R	79	6	7.6	17	21.5	29.1
25–7–36R	17	0	0.0	5	29.4	29.4
25–7–37R	17	2	11.7	6	35.3	47.0
25–7–38R	38	5	13.2	13	34.1	47.3
25–7–39R	69	22	31.8	16	23.2	55.0
25–7–40R	3	0	0.0	3	100.0	100.0
25–7–41R	11	1	9.1	5	45.5	54.6
25–7–42R	25	2	8.0	13	52.0	60.0
25–7–43R	2	0	0.0	1	50.0	50.0
25–7–45R	100	13	13.0	26	26.0	39.0
25–7–47R	118	15	12.5	35	29.6	42.1
25–7–48R	80	19	23.8	26	32.6	56.4
25–7–49R	55	3	5.5	20	36.3	41.8
25–7–50R	69	8	11.6	21	30.4	42.0
25–7–51R	113	11	9.7	30	26.5	36.2
25–7–52R	92	5	5.5	37	40.1	45.6
25–7–53R	9	0	0.0	2	22.2	22.2
25–7–54R	58	17	29.3	20	34.5	63.8
25–7–55R	12	1	8.4	9	75.0	83.4
25–7–56R	26	3	11.6	6	23.1	34.7
Total	1920	311	523.3	563	1416.4	1939.7
Average	47	72.6	13.1	13.1	32.9	45.1

TABLE II—*Continued*

Selection	No. of plants	Killed by wilt		Partially wilted		Total per cent of wilt
		No.	Per cent	No.	Per cent	
175-1-1R	23	0	0.0	6	26.1	26.1
175-1-2R	45	7	15.6	16	35.6	51.2
175-1-3R	42	6	14.3	12	28.3	42.6
175-1-5R	123	20	16.3	27	22.0	38.3
175-1-7R	48	3	6.2	5	10.4	16.6
175-1-8R	30	5	16.7	7	23.2	39.9
175-1-9R	29	6	20.7	8	27.6	48.3
175-1-11R	49	9	18.8	9	18.8	37.6
175-1-12R	68	13	19.2	10	14.7	33.9
175-1-13R	12	1	8.3	5	41.7	50.0
175-1 14R	55	8	14.5	19	34.6	49.1
175-1-17R	35	4	11.4	9	25.8	37.2
175-1-19R	1	1	100.0	0	0.0	100.0
175-1-20R	12	0	0.0	4	33.4	33.4
175-1-21R	4	2	50.0	0	0.0	50.0
175-1-23R	1	0	0.0	0	0.0	0.0
175-1-24R	60	6	10.0	5	8.3	18.3
175-1-30R	33	2	6.0	5	15.2	21.2
175-1-32R	41	6	14.6	4	9.8	24.4
175-1-33R	40	1	2.5	4	10.0	12.5
175-1-35R	38	8	20.0	1	2.6	23.6
175-1-36R	29	0	0.0	5	17.4	17.4
175-1-37R	78	2	3.8	10	12.8	16.6
175-1-38R	52	1	1.9	2	3.8	5.7
175-1-40R	4	0	0.0	1	25.0	25.0
175-1-42R	6	0	0.0	2	33.3	33.3
175-1-43R	63	6	9.5	4	6.4	15.9
175-1-46R	58	7	12.1	4	6.9	19.0
175-1-47R	9	0	0.0	0	0.0	0.0
175-1-48R	10	0	0.0	0	0.0	0.0
175-1-49R	29	4	13.8	5	17.3	31.1
175-1-50R	30	2	6.7	3	10.0	16.7
175-1-52R	62	4	6.5	9	14.5	21.0
175-1-53R	29	3	10.3	2	6.9	17.2
175-1-54R	36	11	30.6	2	5.5	36.1
Total	1284	148	460.3	205	547.9	1012.2
Average	36.8	4.2	13.2	5.9	15.7	29.0
91-1-3R	62	4	6.5	29	46.7	53.2
91-1-4R	117	24	20.6	41	35.0	55.6
91-1-5R	97	21	21.6	33	34.0	55.6
91-1-7R	39	4	10.3	14	35.9	46.2
91-1-8R	119	14	11.8	62	52.1	63.9
91-1-9R	18	2	11.1	5	27.8	38.9
91-1-10R	34	1	2.9	9	26.5	29.4
91-1-11R	69	17	24.6	44	63.7	83.3
91-1-12R	38	2	5.3	6	15.7	21.0
91-1-13R	49	5	10.0	13	26.7	36.7
91-1-14R	46	4	9.6	13	28.2	36.8
91-1-15R	142	13	9.1	38	26.8	35.9
91-1-16R	91	13	14.3	48	52.7	67.0
91-1-17R	143	14	9.8	57	40.0	49.8
91-1-19R	50	5	10.0	31	62.0	72.0
91-1-20R	113	20	17.7	82	72.6	90.3
91-1-22R	24	3	13.0	11	47.9	60.9
91-1-23R	28	0	0.0	13	46.4	46.4
91-1-24R	23	0	0.0	10	43.5	43.5
Total	1302	166	208.2	559	784.2	991.4
Average	78.6	8.8	11.0	28.4	41.4	52.4

TABLE II—*Concluded*

Selection	No. of plants	Killed by wilt		Partially wilted		Total per cent of wilt
		No.	Per cent	No.	Per cent	
74–1–3R	22	3	13.7	10	45.5	59.2
74–1–4R	101	4	4.0	30	30.0	34.0
74–1–5R	138	9	6.5	41	29.8	36.3
74–1–8R	137	4	3.0	48	35.0	38.0
74–1–9R	63	1	1.6	14	22.2	23.8
74–1–10R	64	2	3.1	15	23.5	26.6
74–1–11R	48	4	8.3	17	35.4	43.7
74–1–14R	39	7	18.0	13	33.4	51.4
74–1–15R	72	3	4.1	13	18.1	22.2
74–1–16R	45	2	4.4	16	35.6	40.0
74–1–17R	39	3	7.7	10	25.6	33.3
74–1–19R	94	4	4.2	22	23.4	27.6
74–1–21R	141	20	14.2	62	44.0	58.2
74–1–22R	32	2	6.2	4	12.5	18.7
74–1–23R	27	2	7.4	1	3.7	11.1
74–1–24R	40	4	10.0	12	30.0	40.0
74–1–25R	22	1	4.5	8	36.5	41.0
Total	1124	75	120.9	336	484.2	605.1
Average	66.2	4.4	7.1	19.8	28.5	35.6
II–09–15–1–3R	118	38	32.3	25	21.2	53.5
II–09–15–1–5R	27	8	29.6	6	22.4	52.0
II–09–15–1–6R	98	25	25.5	45	45.9	71.4
II–09–15–1–7R	82	21	25.6	21	25.6	51.2
II–09–15–1–8R	109	29	26.6	18	16.5	43.1
II–09–15–1–10R	3	2	66.7	0	0.0	66.7
Total	437	123	206.3	109	131.6	337.9
Average	73	20.5	34.3	18.2	21.9	56.2

TABLE III

Reaction of Individual Plant Selections from Partially Wilted Plants (PR), in 1919, Selfed in Greenhouse During the Winter of 1919-20, and Planted on Sick Soil in 1920

Selection	No. of plants	Killed by wilt		Partially wilted		Total per cent of wilt
		No.	Per cent	No.	Per cent	
M25-7PR	83	10	12.0	31	37.4	49.4
M25-8PR	56	2	3.6	28	50.0	53.6
M25-9PR	81	25	30.9	42	51.8	82.7
M25-10PR	52	1	1.9	18	34.6	36.5
M25-11PR	14	3	21.4	6	42.9	64.3
M25-12PR	100	12	12.0	27	27.0	39.0
M25-13PR	25	4	17.4	8	34.8	52.2
M25-14PR	80	15	18.7	35	43.8	62.5
M25-15PR	87	32	36.8	44	50.5	87.3
M25-16PR	15	3	20.0	8	53.4	73.4
M25-17PR	19	3	15.8	5	26.4	42.2
Total	612	110	190.5	252	452.6	643.3
Average	55.6	10	17.3	11.9	41.1	58.5
25-7-27PR	44	6	13.6	11	25.0	38.6
25-7-28PR	99	17	17.2	32	32.2	49.4
25-7-29PR	8	1	12.5	3	37.5	50.0
25-7-30PR	76	12	15.7	20	26.3	42.0
Total	227	36	59.0	66	121.0	180.0
Average	56.8	9	14.8	16.5	30.3	45.0
175-1-26PR	66	51	77.3	1	1.5	78.8
175-1-27PR	42	18	42.9	4	9.5	52.4
175-1-29PR	25	4	16.0	4	16.0	32.0
Total	133	73	136.2	9	27.0	163.2
Average	44	24.3	45.4	3.0	9.0	54.4
91-1-26PR	103	8	7.7	38	37.0	44.7
74-1-26PR	50	4	8.0	11	22.0	30.0
74-1-27PR	40	4	10.0	10	25.0	35.0
74-1-28PR	49	2	4.1	11	22.5	26.6
74-1-29PR	128	7	5.5	35	27.2	32.7
Total	267	17	27.6	67	96.7	124.3
Average	66.8	4.3	6.9	16.8	24.2	31.1
II-09-15-1-11PR	27	9	33.3	3	11.1	44.4
II-09-15-1-12PR	33	6	18.4	13	39.4	57.8
II-09-15-1-14PR	142	53	37.3	80	56.4	93.7
II-09-15-1-15PR	60	10	16.7	29	48.3	65.0
II-09-15-1-19PR	114	41	36.0	31	27.2	63.2
II-09-15-1-20PR	95	32	33.6	51	53.6	87.2
II-09-15-1-21PR	120	49	40.9	48	40.1	81.0
Total	591	200	216.2	255	276.1	492.0
Average	84.5	28.6	30.8	56.4	39.5	70.3

TABLE IV

Individual Plant Selections Made in 1919 from Resistant Plants (R), Selfed for Two Generations in the Greenhouse, and Planted on Sick Soil in 1921

Selection	No. of plants	Wilted	
		No.	Per cent
M25–4R	40	40	100.0
M25–5R	61	3	4.9
M25–6R	30	3	10.0
Total	131	46	114.9
Average	43.7	15.3	38.3
25–7–5R	6	0	0.0
25–7–6R	41	3	7.3
25–7–7R	13	0	0.0
25–7–8R	62	9	14.5
25–7–10R	23	1	4.4
25–7–11R	36	3	8.3
25–7–14R	14	1	7.2
25–7–17R	60	6	10.0
25–7–21R	15	1	6.7
25–7–25R	13	3	2.3
25–7–33R	24	2	8.3
25–7–36R	9	0	0.0
25–7–37R	28	5	17.9
25–7–38R	34	6	17.6
25–7–41R	5	0	0.0
25–7–45R	74	1	1.4
25–7–47R	31	2	6.5
25–7–48R	30	6	20.0
25–7–51R	3	2	66.7
25–7–52R	38	8	21.1
Total	559	59	220.2
Average	28	3	11.0
175–1–1R	65	1	1.5
157–1–2R	28	6	21.5
175–1–3R	45	15	33.3
175–1–5R	29	5	17.2
175–1–7R	83	6	7.2
175–1–12R	44	3	6.8
175–1–23R	79	24	30.2
175–1–25R	30	4	13.3
175–1–32R	20	4	20.0
175–1–33R	91	12	13.2
175–1–36R	13	5	38.5
175–1–37R	44	18	40.9
175–1–38R	7	2	28.6
175–1–40R	21	9	42.9
175–1–43R	49	18	36.8
175–1–46R	77	19	24.7
175–1–47R	24	11	45.8
175–1–48R	71	36	50.7
175–1–49R	96	44	45.8
175–1–50R	86	34	39.5
175–1–52R	14	6	42.9
175–1–53R	51	19	37.3
175–1–54R	34	15	44.1
Total	1101	316	682.7
Average	47.9	13.7	29.7

TABLE IV—*Continued*

Selection	No. of plants	Wilted	
		No.	Per cent
91-1-3R	36	29	80.6
91-1-4R	32	23	72.0
91-1-5R	48	34	70.8
91-1-7R	37	23	62.3
91-1-8R	40	23	57.6
91-1-11R	45	31	69.0
91-1-12R	23	12	52.2
91-1-13R	53	38	71.6
91-1-14R	22	16	72.8
91-1-15R	39	14	35.9
91-1-16R	24	16	67.7
91-1-19R	20	17	85.0
91-1-20R	39	24	61.5
91-1-23R	49	13	26.6
91-1-24R	33	18	54.6
Total	540	331	940.2
Average	36	22	62.6
74-1-4R	13	6	46.2
74-1-5R	73	29	39.8
74-1-8R	19	4	21.0
74-1-9R	51	13	25.5
74-1-11R	22	6	27.2
74-1-15R	41	11	26.8
74-1-16R	3	3	100.0
74-1-21R	19	8	42.2
74-1-22R	34	5	14.7
74-1-24R	23	8	34.8
74-1-25R	60	14	23.3
Total	358	107	401.5
Average	32.5	9.5	36.5
II-09-15-1-1R	28	20	10.7
II-09-15-1-3R	52	50	96.2
II-09-15-1-5R	21	21	100.0
II-09-15-1-6R	93	69	64.5
II-09-15-1-7R	38	38	100.0
II-09-15-1-8R	14	14	100.0
II-09-15-1-10R	18	13	72.2
Total	264	225	1069.7
Average	37.7	32.1	77.7

TABLE V

Individual Plant Selections Made in 1919 from Partly Wilted Plants (PR), Selfed for Two Generations in the Greenhouse, and Planted on Sick Soil in 1921

Selection	No. of plants	Wilted	
		No.	Per cent
M25–8PR	62	1	1.6
M25–9PR	24	5	20.0
M25–10PR	44	16	36.4
M25–11PR	20	20	100.0
M25–12PR	90	37	41.2
M25–14PR	34	17	50.0
Total	274	96	249.2
Average	45.7	16	41.5
25–7–28PR	20	1	5.0
25–7–29PR	16	3	18.8
Total	36	4	23.8
Average	18	2	11.9
175–1–26PR	13	2	15.4
175–1–27PR	71	10	14.1
Total	84	12	29.5
Average	42	6	14.8
91–1–26PR	24	12	50.0
74–1–26PR	9	0	0.0
74–1–27PR	34	9	26.5
74–1–28PR	53	20	37.8
74–1–29PR	14	6	42.9
Total	110	35	107.2
Average	27.5	8.8	26.8
II–09–15–1–14PR	57	57	100.0
II–09–15–1–19PR	101	96	95.0
II–09–15–1–21PR	31	30	96.8
Total	189	183	291.8
Average	63	61	97.3

TABLE VI

SUMMARY OF RESULTS OF TWO YEARS' SELECTING AND SELFING

Selection	Parents	No. of individual plant selections		Total No. of plants produced		1920 Percentages			1921 Total percentage wilted	Total average for 1920 and 1921
		1920	1921	1920	1921	Wilted	Partly wilted	Total		
M25	R	5	3	186	131	17.8	42.4	62.0	38.3	50.2
	PR	11	6	612	274	17.4	41.1	61.5	41.7	51.6
	Average					17.6	42.7	61.8	40.0	50.9
25-7	R	43	20	1920	559	12.2	32.9	45.1	11.0	28.1
	PR	4	2	227	36	14.8	30.3	45.1	11.9	28.5
	Average					13.5	31.6	45.1	11.5	28.3
175-1	R	35	23	1284	1101	13.2	15.7	28.9	29.7	29.3
	PR	3	2	133	84	45.4	9.0	54.4	14.8	33.6
	Average					29.3	12.3	42.6	22.3	31.5
91-1	R	19	15	1302	540	11.0	41.4	52.4	62.6	57.5
	PR	1	1	103	24	7.7	37.0	44.7	50.0	47.4
	Average					9.4	39.2	48.6	56.3	52.5
74-1	R	17	11	1124	358	7.1	28.5	35.6	36.5	36.1
	PR	4	4	267	110	6.9	24.2	31.1	26.8	29.0
	Average					7.0	26.4	33.4	32.7	32.6
II-09-15-1	R	6	7	437	264	34.3	21.9	56.2	77.7	67.0
	PR	7	3	591	189	30.8	39.5	70.3	97.3	83.8
	Average					32.6	30.7	63.3	87.5	70.4

TABLE VII

COMPARISON OF PROGENY FROM WILTED (R) AND PARTLY WILTED (PR) FLAX PLANTS

Selection	Year	Parents		Deviation	D^1	$(D^1)^2$
		R	PR			
M25	1920	62.0	61.5	−0.5	1.63	2.65
	1921	38.3	41.7	+3.4	2.27	5.15
25–7	1920	45.1	45.1	0.0	1.13	1.28
	1921	11.0	11.9	+0.9	0.23	0.05
175–1	1920	28.9	54.4	+25.5	24.37	593.89
	1921	29.7	14.8	−14.9	16.03	256.96
91–1	1920	52.4	44.7	−7.7	8.83	77.97
	1921	62.6	50.0	−12.6	13.73	188.51
74–1	1920	35.6	31.1	−4.5	5.63	31.70
	1921	36.5	26.8	−9.7	10.83	117.29
II–09–15–1	1920	56.2	70.3	+14.1	12.97	168.22
	1921	77.7	97.3	+19.6	18.47	341.14
Totals				+13.6		1784.81

Mean deviation = 1.13. Standard deviation, 12.19.

$Z = \frac{1.13}{12.19} = 0.09$. When $Z = 0.1$ and the number of observations = 12, from Student's table it is found that $P = 0.6269$. From this the odds are found to be $\frac{0.6269}{1-0.6269}$ or 1.7 to 1 in favor of PR parents being more susceptible.

Odds of not less than 30 to 1 are regarded as significant.

TABLE VIII

COMPARISON OF PROGENY FROM R AND PR IN SELECTION FROM II–09–15–1 FOR 1920 AND 1921

Selection	Year	Parents		Odds
		R	PR	
II–09–15–1	1920	53.5	44.4	17 to 1 in favor of PR parents being more susceptible.
	1920	52.0	57.8	
	1920	71.4	93.7	
	1920	51.2	65.0	
	1920	43.1	63.2	
	1920	66.7	87.2	
	1921	10.7	100.0	
	1921	96.2	95.0	

TABLE IX

Correlation Table for Total Percentage of Wilt for Individual Plant Selections for 1920 and Percentage of Wilt for 1921

	5	15	25	35	45	55	65	75	85	95	
5	1	1	4	4	3	6	2				21
15		2	1	1	3	2		1			10
25	1	1	3	2	4	2			1		14
35	1	4	1	3	2						11
45	1	1	2	5		1					10
55	1		1		2		2				6
65				1	1		1	1	1	1	6
75				2		2	1				5
85						1		1			2
95					2	3	3		1	1	10
	5	9	12	18	17	17	9	3	3	2	95

Coefficient of correlation = 0.353 ± 0.066.

Table II includes the observations made on the number of plants produced from wilt-free parents in 1919, on the number and percentage killed by wilt, and the number and percentage partially wilted. The record of the number of plants killed outright was kept separate from that of the partially wilted plants in order to see if there was any tendency for resistant parent plants and partially resistant parent plants to produce partially wilted offspring.

Table III is similar to Table II except that it deals with the progeny from partially resistant instead of resistant plants.

It is apparent that, because of the comparatively small number of plants produced and the extremes of the variations, no reliable conclusions can be drawn as to the significance of the results recorded.

Elsewhere a further analysis of Tables II to VII is made in comparison with other results.

Table IV gives the results of the test with the progeny from resistant plants, after two years' selfing in the greenhouse, when tested on sick soil. The total number of plants is given, together with the number of plants wilted and the percentages of wilt.

Table V gives similar results from partially resistant parental plants in 1919.

The percentage of wilt for 1919 was not divided into wilted and partially wilted as in 1918. The percentage of wilted plants was noted, however, as in the preceding year. Notes on the percentages of wilt were taken each week or ten days from the time of emergence to maturity. In 1921 any plants which were so badly wilted that they produced no seed were recorded under wilted. If all partially wilted plants had been included the percentage of total wilt would have been somewhat higher in 1921 than 1920, owing to the very high summer temperatures of 1921. The frequent counts necessitated considerable work but, it was thought that the study of the progress of the disease would justify it. It was originally intended to analyze these data on the sequence of wilting, but there were so few that the analysis was not justified. The records from the 1921 tests indicate slightly more uniformity than do those from the 1920 tests. From these two tables alone few definite conclusions can be drawn.

From Table VI, which summarizes the data on individual plant selections for one and two years' selfing, several interesting conclusions may be drawn. There is little evidence of any correlation between "wilted" and "partly wilted" plants produced in the 1920 tests, or of any correlation with the fact of whether the parents had been resistant (R) or partly resistant plants (PR). Furthermore, an analysis of the entire table indicates that the progeny of "R" and "PR" parents were not essentially different. The only exception to this conclusion might be found in the selections from 11-09-15-1. In order to test this the results for the 1920 and 1921 tests were compared by Student's method and results are given in Table VII. There it is seen that the odds are much less than 30 to 1 for either the analysis of the progeny from all "R" and "PR" plants, or even for those from 11-09-15-1 alone, which are likewise analyzed in Table VIII. It is true that the analysis is not based on a uniform group of figures, but the figures are sufficiently large to make the conclusions fairly reliable. The explanation of the fact that resistant and partly resistant plants or that wilted and partly wilted plants can not be sharply delimited may be that *Fusarium lini* is only a facultative parasite the pathogenicity of which is influenced profoundly by environmental factors. Tisdale (21) has shown clearly how strongly soil temperature affects the development of the disease. Consequently, conditions seem to determine to a considerable extent the amount of injury which any particular plant suffers. It must be borne in mind that resistance to wilt in flax is only relative. The most resistant variety may wilt under severe conditions; while relatively susceptible strains may escape the disease in sick soil under certain favorable conditions. According to the figures in Tables VII and VIII the "R" and "PR" parental forms in any one group possessed approximately the same degree of resistance as was shown by their progeny. Each group seems to possess its own mean, and in comparing it with the mean of the parental form in the group tests in Table XI, this mean has not been fundamentally changed by selections from wilt-resistant strains established by individual selection methods. Equally, there is no question that a new mean has been set for the selections made from M25 and from 11-09-15-1 in which more than 95 per cent wilting occurred uniformly before selection. Both these facts seem to be particularly significant in connection with a pure-line explanation of wilt-resistant varieties.

In Table VI is suggested the possibility of a correlation between the amounts of wilt resulting from these selections in 1920 and 1921.

Accordingly such a correlation table was made, Table IX. The coefficient of correlation was found to be .353 ± .066. In view of the modifying factors that must be taken into consideration in comparing the wilt produced under field conditions in any one year with that of another year, this correlation appears to be quite significant. This brings out more forcibly perhaps than any other single analysis of these individual plant selection studies, the possible pure-line basis for interpreting the inheritance of wilt resistance.

A STUDY OF VARIATIONS WITHIN INDIVIDUAL SELECTIONS

Several individual selections made in 1919 were reselected in 1920. This was done within selections made in 1919 from non-selected varieties, M25 and 11-09-15-1. Each plant that produced seed in these selections was saved, classified, and labeled as wilt-free (R), or as partly wilted (PR). The seed from each plant was sown in a five-foot row in the plant pathology plots in the spring of 1921. In every case reselection seemed to be without effect. These plant rows, while varying considerably as might be expected in dealing with wilt resistance, were remarkably uniform as a series. Each series, however, differed markedly from the neighboring series, even when both were 1919 selections from the same variety. There undoubtedly would not have been such great uniformity if a larger number of 1919 selections had been taken for further analysis, as some of these probably would have proved to be heterozygous with segregation resulting. A most striking example of the uniformity of the reaction in the reselections is shown in Plate IV. On the left is the progeny of M25-14PR, which was obtained from eight plants, seven of which were marked "partly resistant," in 1920. On the right is shown the progeny from M25-5R, a most vigorous plant that stood out in sharp contrast to the rest of the susceptible plants when it was originally selected in 1919. Plate III shows this original selection. Seed was obtained from 43 plants which it produced in 1920. Each of these, 27 of which appeared to be wilt free, were likewise planted in five-foot rows. The average percentage of wilt from these was 29.7, with the progeny from (R) and (PR) indistinguishable. The remarkable contrast between the progeny from M25-5R and M25-14PR is shown in Plate IV.

These studies seem to indicate at least two facts. (1) The original selection is the important one; subsequent selections, unless the plants are heterozygous, are of no avail in changing the resistance of the selection. There are different degrees of resistance in the original selection. M25-14PR produced some seed in 1920, and the selfed selection from the greenhouse produced seventeen plants in 1921 which, while not notably vigorous, produced some seed. Certain very susceptible varieties never produce plants that are able to grow beyond the very young seedling stage in sick soil. In accordance with Tisdale's (22) interpretation of resistance on the basis of multiple factors, it is probable that M25-14PR possesses only a part of them. (2) Resistance is not a character acquired by plants only after having been grown for several years on sick soil. Such selections as M25 appear vigorous and resistant as they occur scattered over the field the first year they are grown on sick soil. These retain their resistance in the immediate or successive progeny, and if they are "pure," as they appear to be in certain cases, resistance is not further built up and is not accumulative by an association of the host and the pathogene as has been commonly supposed to be the case.

LIMITS OF SELECTION

The preceding tests have indicated some of the limits of selection. It has been a rather common opinion that resistance could be developed in any variety by selection; Bolley thought (5, p. 179) (6, p. 181) that by growing an extremely susceptible variety on lightly infested soil, making selections there, and then transferring these successively to increasingly heavily infested soils, a high degree of resistance could be built up. This has not been thoroly tested in the experiments recorded here, but observations do not support this opinion. Seed of C. I. Nos. 186 and 190 grown at Mandan, North Dakota, were furnished by the United States Department of Agriculture. Several rows of these were planted in the plant pathology plots in 1919. One hundred per cent of the plants wilted within two weeks after emerging from the soil. There was absolutely no indication of resistance, quite in contrast to Minn. No. 25 which was grown as a susceptible check. The latter usually developed from 95 to 100 per cent wilt, with an occasional normal plant; and frequently several partly wilted plants which produced seed. The wilting usually occurred throughout the season, a few plants being killed in the seedling stage and others following. This might be taken as an indication of a certain degree of resistance. There were no such indications in C. I. 186 and 190. However, the two latter were planted in a field in which so little wilt developed that Minn. No. 25 produced a fairly normal crop. Only a few plants of C. I. 186 and C. I. 190 survived. These were saved and seed was sown in sick soil in the plant pathology plots the following year. Again they did not get beyond the seedling stage. Three of the plants which survived from C. I. 186 were found later to be rogues which apparently resulted from a mechanical mixture of the seed. They were of a dwarf, much branched, almost procumbent type, highly resistant, but they in no way resembled C. I. 186.

These observations, in conjunction with the more detailed studies of individual selections such as were noted for M25-5R and M25-14PR, led the writer to conclude that resistance is either present in a variety or absent, and that if absent it can not be acquired gradually by the association of the plant with the fungus. It must be remembered in this connection that true resistance to a disease like flax wilt and disease-escaping qualities are not always easily distinguishable; but at least they should not be confused.

EFFECT OF CLEAN SOIL ON LOSS OF WILT RESISTANCE

Whether or not wilt-resistant varieties of flax are able to retain their resistance only when grown continuously in the presence of the disease-producing organism, is a most important question. It is of profound fundamental interest in relation to the nature of the inheritance of wilt resistance. It is obviously of much practical importance also. Bolley's (6, p. 177-78) studies of flax wilt led him to conclude that the growing of wilt-resistant varieties on non-infested soil resulted in the loss of the wilt-resistant qualities. In view of this it was advocated that a sick soil seed plot should be maintained. This peculiarity of disease resistance has been the subject of considerable discussion and interest among investigators. Jones, Walker, and Tisdale (15, p. 31), point out that in cabbage yellows, which is caused by *Fusarium conglutinans* Wollenw., it seems inevitable that in all the resistant strains there is a tendency to progressive reversion with a consequent loss of disease resistance which can only be met by continued selection from plants grown on sick soil. Their tests, however, with western seed produced on clean soil showed little or no loss of resistance.

In order to determine whether the growth of resistant varieties of flax on clean soil resulted in the loss of resistance, wilt-resistant selections which had been produced by both bulk and individual selection methods were grown on clean soil in isolated rows in corn plots on non-infested soil. Each year a part of the seed produced was saved for subsequent growth on clean soil and part was brought back to the plots to be compared with the corresponding selection which had been grown continuously on sick soil.

The results for two years' growth on clean soil are analyzed in Table X. This comparison is based on yields only. No appreciable difference is evident between the clean-soil series and the sick-soil series after two years' growth on clean soil. Consequently the analysis for 1920 was not made on the basis of wilt also. In one case the slight odds are actually in favor of the clean-soil series, the two latter are slightly in favor of the sick-soil series. However, neither of the differences may be considered as significant; for the odds, to be considered significant, should be thirty to one, while here they are in no case more than four to one.

TABLE X

COMPARISON OF RESULTS OF 1920 TEST FOR LOSS OF WILT RESISTANCE ON CLEAN SOIL FOR TWO YEARS COMPUTED BY STUDENT'S METHOD

	Clean soil	Sick soil		
Selection	Yield per acre, Bu.	Yield per acre, Bu.	Odds	In favor of
Plot I–25 (Bulk selection)	5.35	7.78	3.8:1	Sick soil
	8.00	14.90		
	4.10	6.02		
Plot III–175–1	14.53	10.42	1.4:1	Clean soil
	5.33	7.13		
	3.42	4.42		
Plot IV–25–7	4.63	6.25	3.2:1	Sick soil
	10.30	9.60		
	3.39	6.02		

Table XI gives the results of the 1921 tests for the selections grown continuously on sick soil. Table XII gives the corresponding results for the same selections which had been grown on clean soil for three years (with the exceptions given in the footnote) and brought back for test on sick soil in 1921. Table XIII gives a comparison of Tables XI and XII on the basis of yield. The probable error was computed by the simplified "Minnesota method" (12). Table XIV gives a similar comparison on the basis of percentage wilted. The percentages of wilt were determined by careful counts made at regular intervals throughout the growing season. Whether based on the amount of wilt or on yield, the differences are not significantly greater than the probable error of the differences except in the case of II-09-15-1, which is greater by a significant amount in both tables; and for Plot II 25-1, which on the basis of yield varies markedly in favor of clean soil because it was necessary to use 1918 seed for the sick-soil series. This seed germinated very poorly, producing only a few plants, as is shown in Table XII. On the basis of the percentage of wilt there is no evidence of a significant difference.

The marked differences in favor of sick soil in this one case (II-09-15-1) do not in reality indicate loss of wilt resistance due to growth on clean soil, but rather indicate the effect of bulk selection in producing resistance by growth on sick soil. In checking up the history of this selection which had been produced by the section of plant breeding for its desirable agronomic characters (see Table I), it was found that the first year of its growth on sick soil was at Crookston. There the soil on which it was grown in 1919 produced in reality little wilt—only 10 per cent in this variety. In the same season there was from 90 to 95 per cent wilt in the plant pathology plots at University Farm. Practically no seed was produced in 1919 on these plots. Consequently it was necessary to use Crookston seed for planting both series in 1920. It seems that the 1921 test, comparing the results from sick soil with those from clean soil, are really nothing more than a determination of the reduction in percentage of wilt by means of natural selection resulting from one year's growth on very sick soil when compared with its parental type. The inevitable conclusion is that wilt-resistant selections do not lose their resistance when grown on clean soil. This seems to be true regardless of the degree of resistance and of the method by which it was obtained. If the variety has not become uniform for resistance, natural selection merely stops and, in the case of a fairly close-fertilized crop, the proportion of resistant and susceptible plants does not change.

TABLE XI

RESULTS OF 1921 TESTS FOR EFFECT OF CLEAN SOIL ON LOSS OF WILT RESISTANCE—SICK-SOIL SERIES IN WHICH THE WILT-RESISTANT SELECTIONS HAVE BEEN GROWN CONTINUOUSLY ON SICK SOIL

Selection	Row	No. of plants	No. wilted	Per cent wilted	Yield per acre, Bu.
Plot I 25*	5	472	212	45	2.01
	65	680	311	44	3.65
	116	492	132	27	5.23
Average	...	...	...	39	3.63
Plot IV 25–7*	11	293	103	35	1.51
	71	355	144	41	4.68
	122	358	59	16	4.72
Average	...	...	...	31	3.60
Plot III 175–1†	17	663	88	12	9.83
	77	353	83	15	11.45
	128	576	64	11	7.03
Average	...	...	...	13	9.44
Plot II 91–1*	23	491	90	18	8.33
	83	353	77	22	5.83
	134	375	66	18	4.58
Average	...	...	...	19	6.25
Plot IV 74–1*	29	413	159	39	4.68
	89	586	294	50	2.81
	140	512	164	32	3.34
Average	...	...	...	40	3.61
Plott II-09-15-1‡	35	590	242	41	2.97
	95	436	205	47	1.47
	146	471	238	50	2.09
Average	....	...	...	46	2.18
Plot II 25–1*	41	121	50	41	1.91
	101	60	28	47	0.60
	152	92	24	26	0.74
Average	....	...	...	38	1.08§
Plot VI 25‖	47	297	166	56	2.83
	107	559	320	57	0.81
	158	418	230	55	2.25
Average	....	...	...	56	1.96

* Grown on sick soil on plant pathology plots of University Farm continuously since 1914.

† Grown on sick soil on plant pathology plots of University Farm continuously since 1915.

‡ Grown at Crookston in 1919 on practically clean soil when there was only about 10 per cent of wilt in this variety. Grown on sick soil of the plant pathology plots, University Farm, in 1920 and 1921.

§ Grown from 1918 seed; germination very poor.

‖ Grown on practically clean soil at Crookston in 1919 and on sick soil in 1920 and 1921.

TABLE XII

RESULTS OF 1921 TESTS FOR EFFECT OF CLEAN SOIL ON LOSS OF WILT RESISTANCE—CLEAN-SOIL SERIES IN WHICH WILT-RESISTANT SELECTIONS HAVE BEEN GROWN FOR THREE YEARS, WITH EXCEPTIONS NOTED AWAY FROM SICK SOIL

Selection	Row	No. of plants	No. wilted	Per cent wilted	Yield per acre, Bu.
Plot I 25	8	562	242	41	2.71
	68	609	334	55	3.12
	119	583	135	23	5.27
Average	....	...	...	39	3.70
Plot IV 25–7	14	688	331	41	2.80
	74	675	345	51	3.55
	125	568	48	8	5.38
Average	....	...	...	33	3.91
Plot III 175–1	20	459	81	13	11.71
	80	388	50	11	9.40
	131	509	73	12	8.04
Average	....	...	...	12	9.72
Plot II 91–1*	26	914	149	16	6.60
	86	703	95	13	4.51
	137	402	135	34	4.15
Average	....	...	...	21	5.09
Plot IV 74–1*	32	711	211	30	4.29
	92	904	328	36	4.11
	143	617	261	42	2.50
Average	....	...	...	36	3.63
Plot II–09–15–1†	38	1143	842	74	1.64
	98	987	719	73	1.39
	149	554	516	93	0.29
Average	....	...	...	80	1.11
Plot II 25–1	44	845	328	39	6.33
	104	378	80	24	3.28
	155	338	133	39	4.60
Average	....	...	...	34	4.73
Plot VI 25‡	50	889	504	57	3.33
	110	657	442	67	1.56
	161	655	235	36	2.83
Average	....	...	...	53	2.57

* Grown on clean soil for one year, 1920, before being brought back onto sick soil of the plant pathology plots for comparison with the sick-soil series.

† A non-selected variety grown on practically clean soil at Crookston in 1919 and 1920.

‡ Non-selected Minn. No. 25 grown on clean soil continuously, so far as the records are obtainable.

All the other selections were grown on clean soil for three years, 1918, 1919, and 1920, before being brought back onto sick soil of the plant pathology plots for comparison with the sick-soil series.

TABLE XIII

SUMMARY OF DIFFERENCES IN MEANS OF YIELD WITH RESPECT TO EFFECT OF CLEAN SOIL ON LOSS OF WILT RESISTANCE

Selection	Average yield for series, Bu.		Differences in means, Bu.	Odds against occurrence of existing deviation*
	Clean soil	Sick soil		
Plot I 25	3.70 ± 0.47	3.63 ± 0.46	0.07 ± 0.7	Less than 1 to 1
Plot IV 25–7	3.91 ± 0.49	3.60 ± 0.45	0.31 ± 0.7	Less than 1 to 1
Plot III 175–1	9.72 ± 1.24	9.44 ± 1.19	0.28 ± 1.7	Less than 1 to 1
Plot II 91–1	5.09 ± 0.64	6.25 ± 0.79	1.16 ± 1.0	About 1.3 to 1
Plot IV 74–1	3.63 ± 0.46	3.61 ± 0.45	0.02 ± 0.6	Less than 1 to 1
Plot II–09–15–1	1.11 ± 0.14	2.18 ± 0.27	1.07 ± 0.3	About 60 to 1
Plot II 25–1	4.73 ± 0.60	1.08 ± 0.14	3.65 ± 0.6	About 20,000 to 1
Plot VI 25	2.57 ± 0.32	1.96 ± 0.25	0.61 ± 0.4	About 2.3 to 1

* Computed in accordance with "a table for estimating the probable significance of statistical constants," by Raymond Pearl and John Rice Miner, *In* Maine Agr. Exp. Sta. Bul. 226, pp. 85-88, March 1914.

TABLE XIV

SUMMARY OF DIFFERENCES IN MEANS OF WILT WITH RESPECT TO EFFECT OF CLEAN SOIL ON LOSS OF WILT RESISTANCE

Selection	Average per cent of wilt for series		Differences in means, per cent	Odds against occurrence of existing deviation
	Clean soil	Sick soil		
Plot I 25	39 ± 3.9	39 ± 3.9	0 ± 5.5	Less than 1 to 1
Plot IV 25–7	33 ± 3.3	31 ± 3.1	2 ± 4.5	Less than 1 to 1
Plot III 175–1	12 ± 1.2	13 ± 1.3	1 ± 1.8	Less than 1 to 1
Plot II 91–1	21 ± 2.1	19 ± 1.9	2 ± 2.8	Less than 1 to 1
Plot IV 74–1	36 ± 3.6	40 ± 4.0	4 ± 5.4	About 1 to 1
Plot II–09–15–1	80 ± 8.0	46 ± 4.6	34 ± 9.2	About 8 to 1
Plot II 25–1	34 ± 3.4	38 ± 3.8	4 ± 5.1	About 1 to 1
Plot VI 25	53 ± 5.3	56 ± 5.6	3 ± 7.7	Less than 1 to 1

EFFECT OF TIME OF PLANTING ON DEVELOPMENT OF FLAX WILT

Observations made on flax planted at various times seemed to indicate that the time of planting had considerable effect on the amount of wilt in both resistant and susceptible strains. In order to test this and to see what practical application it might have, particularly its effect on resistant varieties, time-of-planting tests were made in 1920 and in 1921. Results are given in Tables XV and XVI, and illustrated in Plates X to XIV inclusive.

These results show a marked relationship between wilt resistance and environmental conditions. Perhaps the erroneous impressions that have arisen regarding the nature of resistance in flax have been in part due to failure to appreciate this relationship. It will be noted from

Tables XV and XVI that the resistant varieties, when sown late, may be so severely affected by wilt that they produce practically no seed. On the other hand, a moderately susceptible variety like Minn. No. 25, when sown early, may so nearly escape the wilt that a fair crop is produced even on extremely sick soli.

The explanation of these results is undoubtedly to be found in the optimum temperature relations of the host and the parasite. Tisdale (21, 22) found that the optimum temperature range for the growth of the fungus was higher than that for the host. This, applied to field conditions, would mean that early-planted flax would grow more nearly under its most favorable conditions during the very early summer, and consequently be more vigorous and better able to withstand the infection. For later plantings this would not be true and, furthermore, the fungus would find its most favorable conditions of growth at the time when the host was not so vigorous. The practical significance of these results is apparent.

TABLE XV

Effect of Time of Planting on Development of Flax Wilt in Two Wilt-Resistant Selections. Planted on Sick Soil, University Farm, 1920

Selection	Date of planting	Per cent wilt	Yield per acre, Bu.
Plot IV 25–7	April 27	2	10.93
	May 7	5	8.48
	May 18	7	6.33
	May 30	50	0.46
Plot III 175–1	April 27	2	10.80
	May 7	5	7.77
	May 18	7	7.35
	May 30	40	2.38

TABLE XVI

Effect of Time of Planting on Development of Flax Wilt. Planted on Sick Soil, University Farm, 1921

Selection	Date of planting	Per cent wilt	Yield per acre, Bu.
Minn. 25 Non select	April 18	81	3.94
	May 1	84	1.54
	May 15	87	0.36
	June 1	94	0.36
Plot IV 25–7	April 18	28	10.25
	May 1	46	6.16
	May 15	53	1.16
	June 1	88	0.96
Plot III 175–1	April 18	11	9.79
	May 1	20	4.94
	May 15	12	4.89
	June 1	76	Undetermined

YIELD TESTS OF MINNESOTA WILT-RESISTANT SELECTIONS

The alarming decrease in flax acreage and in the production of linseed in this country which, as has been pointed out, is largely due to the presence of flax wilt, calls attention to the importance of finding some method of controlling the disease. Seed treatment, as was pointed out by Bolley (1, 2, 3), is important in lessening the amount of inoculum that may be carried to new lands. However, with the most careful seed treatment, this source of infection can not be entirely eliminated. Laboratory tests here have shown that the fungus can frequently be isolated from apparently sound seed that has been treated for five minutes with 1 to 1000 mercuric chloride. Furthermore, the available supply of clean land is decreasing each year. *Fusarium lini*, which is an accomplished saprophyte, persists for so long in the soil that crop rotation will not solve the problem satisfactorily. In 1920 observations were made at Crookston on a six-year crop rotation plot which included flax. The amount of wilt in one of these fields, which had grown one crop of flax six years previously, was striking when compared with the amount in the same variety on new land. Wilt was, of course, not nearly as serious as it would have been had flax followed flax, but the damage was considerable. Hope, therefore, centers primarily on the control of wilt by means of resistant varieties. Bolley demonstrated that this solution was practicable. Stakman et al. (20) confirmed Bolley's results and published the results of one year's tests of selections produced at the Minnesota station. Their results suggested that certain of these wilt-resistant selections yielded well. The criticism is sometimes made that resistant varieties do not yield as well on clean soil as do certain susceptible varieties. It is obvious that the ultimate test of the value of a variety is its ability to yield well.

The writer, through the courtesy of various co-operators, has been enabled to continue these experiments for four years. Table XVII gives the results of four years' tests on the extremely sick soil of the plant pathology plots. These yields were obtained from triplicated series of three rows each. The yields were computed from the central row of each series. Unfortunately, in 1919, the yields for Chippewa and Winona were based on a single determination. The last column gives the odds for comparison with Student's method which is used throughout in making comparisons for each table where it is applicable. Odds of thirty to one are considered significant.

Table XVIII gives the yields of the resistant selections and varieties on sick soil at Waseca for three years. Yields in this case were obtained from the central rows of triplicated three-row series.

Table XIX gives the results of similar tests for four years on sick soil at Mandan, North Dakota. These data were furnished by the Office of Cereal Investigations, United States Department of Agriculture. The yields were based on five-foot rows in triplicate.

It will be seen that in all the tests made in extremely sick soil, Winona and Chippewa yielded more, except at Waseca, where Chippewa did not yield quite so well. The odds in favor of Winona at University Farm and at Waseca are decidely significant.

Table XX gives the results of two years' tests on clean soil in the plant breeding nursery at University Farm. Yields are based on the central rows of triplicated three-row series.

Table XXI compares with Table XX, except that the tests are made on clean soil and the yields are based on triplicated seventeen-foot rows at Mandan. These data also were kindly furnished by the Office of Cereal Investigations.

Table XXII gives the results of two years' tests at Fargo, North Dakota, on land that had practically no wilt for these two years. These data were furnished through the kind co-operation of the North Dakota Agriculural College, and were based on triplicated rod rows.

Table XXIII gives the results of three years' tests at Crookston, Minn. These tests were made on soil that produced practically no wilt. Yields were obtained from the central row of each triplicated series of three rows, thirty feet long.

Table XXIV gives the results of one-fortieth acre field tests made by the agronomy department at University Farm. The soil was inoculated by the writer shortly after the plants had emerged, by growing the organism on sterilized wheat seed in large jars. After the organism had spread throughout the wheat, this was scattered over the field. The very susceptible varieties which were also grown developed much wilt, but not enough to make this a critical test of resistance comparable to those of the sick soil of the plant pathology plots. Hence in the summary table these results are grouped with the clean soil tests.

Table XXV gives the results of one-fortieth acre field tests on clean soil. These tests were made by the agronomy department and the data on yield were kindly furnished by them.

Table XXVI is a summary of the averages obtained from Tables XVII to XXV. From this it appears that the row tests gave much lower yields than did the one-fortieth acre plots. A comparison of these summary results is made by the Student's method in Table XXVII. Winona, Minn. No. 182 (175-1), appears to be pronouncedly superior to any other variety tested on sick soil. Chippewa, Minn. No. 181 (25-7), apparently yields as well as N. D. R. 114. On clean soil all three of these varieties yield about the same. Selection 91-1, Minn. No. 188, seems to yield exceptionally well on clean soil and averages practically as high as Chippewa or N. D. R. 114 on sick soil.

It was noted in the field that Chippewa was quite resistant to rust of flax caused by *Melampsora lini*.

TABLE XVII

YIELD TESTS OF SELECTED FLAX ON SICK SOIL, UNIVERSITY FARM (TEN-FOOT ROWS)

Selection	1919		1920		1921		1922		4-yr. Av.		Odds
	Per cent wilt	Yield Bu.	Per cent wilt	Yield Bu.	Per cent wilt	Yield Bu.	Per cent wilt	Yield Bu.	Per cent wilt	Yield Bu.	
N. D. R. 114	29	2.65	48	6.01	32	5.06	20	3.84	32.30	4.39	Check
Chippewa (25–7)	4	8.66	11	9.02	31	3.60	10	3.22	14.00	6.13	9.80:1
Winona (175–1)	4.6	7.03	13	7.36	13	9.44	10	5.89	10.15	7.18	77.74:1
Plot 91–1	37	1.89	15	9.88	19	6.25	15	5.09	21.50	5.78	8.22:1
Plot 74–1	22	2.14	23	7.69	40	3.61	25	2.21	27.50	3.91	10.01:1
Plot II–09–15–1	91	0.00	55	3.02	46	2.18	30	3.16	43.60*	2.79*	

* Three-year average.

TABLE XVIII

YIELD TESTS OF SELECTED FLAX ON SICK SOIL, AT WASECA (THIRTY-FOOT ROWS)

Selection or variety	Yield per acre, Bu.				Odds
	1919	1920	1921	3-yr. av.	
N. D. R. 114	....	6.45	6.18	6.33*	......
Chippewa (25–7)	1.81	4.35	4.55	3.57	Check
Winona (175–1)	3.24	11.93	9.38	8.18	37.02:1
Plot II 91–1	2.61	7.86	1.18	4.15	3.57:1
Plot IV 74–1	0.90	2.70	0.95	1.52	33.22:1
Plot II–09–15–1	0.11	1.68	1.02	0.94	

* Two-year average.

TABLE XIX

YIELD TESTS OF SELECTED FLAX AT MANDAN, NORTH DAKOTA, ON SICK SOIL (FIVE-FOOT ROWS)*

Selection or variety	Yield per acre, Bu.					Odds
	1919	1920	1921	1922	Average	
N. D. R. 114	2.6	4.3	1.9	12.0	5.2	Check
Chippewa (25–7)	1.0	5.3	2.4	15.8	6.1	4.31:1
Winona (175-1)	3.1	7.9	3.0	17.0	7.8	12.08:1
Plot II 91–1	1.2	3.0	2.4	10.2	4.2	17.21:1
Plot IV 74–1	1.7	2.7	2.5	15.1	5.5	1.53:1
Plot II–09–15–1	0.0	3.3	0.9	10.0	3.6	......

* These tests were made by the Office of Cereal Investigations, U. S. D. A., and the data were kindly furnished by them.

TABLE XX

YIELD TESTS OF SELECTED FLAX ON CLEAN SOIL AT UNIVERSITY FARM (SIXTEEN-FOOT ROWS)*

Selection or variety	Yield per acre, Bu.		
	1919	1920	Average
Chippewa (25–7)	2.44	9.60	6.02
Winona (175–1)	0.55	8.40	4.48
Plot II 91–1	5.58	10.79	8.19
Plot IV 74–1	2.80	9.10	5.95
Plot II–09–15–1	2.37	10.91	6.64

* Grown in plant breeding nursery.

TABLE XXI

YIELD TESTS OF SELECTED FLAX ON CLEAN SOIL AT MANDAN, NORTH DAKOTA

(ROD ROWS)*

Selection or variety	Yield per acre, Bu.				Odds
	1919	1920	1922	3-yr. av.	
N. D. R. 114	4.2	2.7	12.9	6.6	Check
Chippewa (25–7)	4.0	2.1	14.8	7.0	2.22:1
Winona (175–1)	5.5	2.7	14.2	7.5	1.34:1
Plot II 91–1	5.6	2.9	13.6	7.4	12.15:1
Plot IV 74–1	4.8	1.9	15.4	7.4	4.11:1
Plot II–09–15–1	2.6	2.0	13.0	5.9	

* These tests were made by the Office of Cereal Investigations, U. S. D. A., and the data were kindly furnished by them.

TABLE XXII

YIELD TESTS OF SELECTED FLAX ON PRACTICALLY CLEAN SOIL AT FARGO, NORTH DAKOTA (ROD ROWS)*

Selection or variety	Yield per acre, Bu.		
	1921	1922	Average
N. D. R. 114	9.2	15.3	12.3
Chippewa (25–7)	7.2	16.3	11.8
Winona (175–1)	8.1	16.0	12.1
Plot II 91–1	6.6	19.9	13.3
Plot IV 74–1	5.4	15.4	10.4

* These tests were made by the North Dakota Agricultural College. The data were furnished by them.

TABLE XXIII

Yield Tests of Selected Flax at Crookston on Comparatively Clean Soil (Thirty-Foot Rows)

Selection or variety	Yield per acre, Bu.				Odds
	1919	1920	1921	Average	
N. D. R. 114	....	8.75	2.58	5.67	......
Chippewa (25–7)	14.92	5.02	2.16	7.37	4.74:1
Winona (175–1)	6.32	4.63	3.50	4.82	6.69:1
Plot II 91–1	13.60	6.51	3.58	7.90	3.23:1
Plot IV 72–1	14.41	7.65	2.72	8.26	Check
Plot II–09-15–1	5.25	8.17	2.19	5.20	3.98:1

TABLE XXIV

Yield Tests* of Selected Flax on Partially Sick Soil† at University Farm in 1921 (One-Fortieth Acre Plots)

Selection or variety	Yield per acre, Bu.
N. D. R. 114	14.0
Chippewa (25–7)	13.4
Winona (175–1)	13.2
Plot II 91–1	16.8
Plot IV 74–1	11.6

* This test was made by the agronomy department, University Farm, and the data on yield were furnished by them.

† The soil was inoculated by the writer shortly after the plants emerged. Wilt developed quite heavily on White Blossom Dutch, an extremely susceptible variety, but was not heavy enough to give a reliable differential test.

TABLE XXV

Yield Tests of Selected Flax at Crookston, Minn., on Clean Soil (One-Fortieth Acre Plots)*

Selection or variety	Yield per acre, Bu.		
	1921	1922	Average
N. D. R. 114	7.06	13.91	10.49
Chippewa (25–7)	6.68	12.60	9.64
Winona (175–1)	8.09	14.57	11.33
Plot II 91–1	8.09	18.99	13.54
Plot IV 74–1	9.72	13.50	11.61

* These tests were made by the agronomy department, University Farm, and the data were furnished by them.

TABLE XXVI

Summary of Averages from Tables XVII to XXV

Station	No. of years	Group	N.D.R. 114	Chippewa	Winona	91–1	74–1
		Sick soil					
University Farm.....	4	Row tests	4.39	6.13	7.18	5.78	3.91
Waseca	3	Do	6.33*	3.57*	8.18	4.15	1.52
Mandan............	4	Do	5.20	6.10	7.80	4.20	5.50
Average		...	5.31	5.27	7.72	4.71	3.64
		Clean soil					
University Farm.....	2	Row tests	....	6.02	4.48	8.19	5.95
Mandan............	3	Do	6.60	7.00	7.50	7.40	7.40
Fargo	2	Do	12.30	11.80	12.10	13.30	10.40
Crookston	3	Do	5.67	7.37	4.82	7.90	8.26
Average		...	8.19	8.05	7.23	9.20	8.00
		Clean soil					
University Farm.....	1	1/40 A. plot	14.00	13.40	13.20	16.80	11.60
Crookston	2	Do	10.49	9.64	11.33	13.54	11.61
Average		...	12.25	11.52	12.27	15.17	11.61

* Two-year averages.

TABLE XXVII

Comparison of Summaries of Yield Tests from Table XXVI by Student's Method

Selection	Tested on	Odds	In favor of
(N. D. R. 114) Check.........	Sick soil	Check	
Chippewa	Do	1:1	
Winona	Do	129:1	Winona
91–1	Do	3:1	N. D. R. 114
74–1	Do	4:1	N. D. R. 114
	Clean soil		
(N. D. R. 114) Check.........	(rows and plots)	Check	
Chippewa	Do	1:1	
Winona	Do	1:1	
91–1	Do	68:1	91–1
74–1	Do	1:1	

DISCUSSION AND CONCLUSIONS

Flax wilt undoubtedly has been one of the most important limiting factors in flax production in the United States. On account of the devastation caused by this disease, the center of flax production has continually moved westward. Flax should not be grown on the same soil more than once every ten or twelve years unless resistant varieties are available; in fact, it is questionable whether it can be grown that often. There seems to be evidence that the organism causing flax wilt may be present in most soils in those regions in which flax has ever been grown extensively. As *Fusarium lini* can live in the soil almost indefinitely as a saprophyte, and as it may persist within shriveled seeds or apparently sound seeds of flax, it is almost impossible to control it by ordinary methods of crop rotation or seed treatment. For this reason it has become necessary to attempt to develop resistant varieties.

Pioneer work on the control of flax wilt by means of resistant varieties was done by Broekema and by Bolley. Bolley demonstrated clearly that wilt-resistant strains could be obtained rather easily. He was inclined to think that resistance was developed in a variety as a result of constant association with the pathogene. In other words, a susceptible variety might be immunized artificially by association with *Fusarium lini*. This would be roughly comparable with artificial immunization in animals. But even in animals there is little or no evidence of such immunity being inherited. Presumably some toxin produced by the parasite promoted the production of anti-bodies in the host plant. Bolley was of the opinion that the degree of resistance was proportional to the length of time during which the strain or variety had been exposed to the disease. Furthermore, the permanence of the resistance would be roughly proportional to the length of time during which the immunizing process had operated. Practically, this meant that resistant strains could be developed in any variety of flax, but that several years might be required to produce these resistant strains. Naturally, resistant flax would lose its resistance if it was grown on clean land. The resistance of flax to wilt, then, would be quite different from the resistance to other plant pathogenes, because artificial immunity is practically unknown, if indeed it occurs at all in plants.

It is quite true that the wilt resistance of flax is only relative. Plants can be predisposed to attack and they can be protected against attack. The pathogene is greatly affected by temperature. Furthermore, the flax plant is rather sensitive to high temperatures, and therefore plants which normally are resistant under good growing conditions may be susceptible under poor growing conditions. The pronounced effect of soil temperature was shown first by Tisdale, and the writer has demonstrated clearly that the amount of wilt which develops in either a resistant or a susceptible strain may be very greatly affected by soil temperatures. High soil temperatures are conducive to the development of a great deal of wilt because they are unfavorable to the flax plant and very favorable for the growth of the pathogene. The converse is true of low soil temperatures. When planted late in the season, when the soil temperatures are high, a resistant variety may be injured severely by wilt. On the other hand, a susceptible variety, sown early in the season when the soil temperatures are low, may produce a good crop. It is quite probable that the relative resistance of flax strains to wilt and the fact that the course of the disease is influenced so greatly by environmental conditions have obscured somewhat the true facts in connection with the production of wilt-resistant strains of flax.

All the results which the writer has obtained indicate rather clearly that wilt resistance is not built up by exposing plants to disease. It is thought that the resistant genotypes, if they may be called such, already exist in any variety in which there are resistant plants. When such varieties are sown on sick soil under temperature conditions favorable to the development of the disease, the non-resistant plants are eliminated and the resistant ones survive. Individual plant selection seems to be more efficacious than bulk selection simply because in practicing individual selection only the most resistant plants are saved. When bulk selections are made, however, the highly resistant and moderately resistant plants are saved as well as those which have merely escaped the disease on account of some fortuitous circumstances. The seed, therefore, consists of seed from resistant individuals, from moderately resistant ones, and from those which are susceptible but merely escape the disease. Naturally, when this seed is sown on sick soil, the resultant crop is not uniformly resistant. The evidence is perfectly clear that the selection of resistant flax strains consists merely in isolating genotypes which were resistant from the very beginning. Constant growing on sick soil, or on any other soil for that matter, does not change the genotypic composition of the plant with respect to wilt resistance. It would not be expected, therefore, that growing plants on clean soil would result in a loss of resistance. Experimental and observational evidence confirm this opinion.

Resistant varieties of flax which had been grown on clean soil for three years were just as resistant as strains of the same variety grown continuously on sick soil. It must be remembered, of course, that when a strain of flax is grown continuously on sick soil, the susceptible types are eliminated and only the most resistant remain. On the other hand, when a strain is grown on clean soil, the susceptible types are not eliminated. It may appear, therefore, that a strain loses its resistance when grown on clean soil. As far as this carries any implication, however, that the germinal constitution of the strain with respect to wilt resistance is changed, the idea is erroneous. Resistance to *Fusarium lini* is an inheritable character comparable with any other genetic character.

In the course of the investigations, extensive observations were made on Chippewa, Minn. No. 181; and Winona, Minn. No. 182, both of which were selected originally by Stakman and Aamodt. The former was selected from Primost, Minn. No. 25, and is designated in the tables as 25-7, or as Plot IV 25-7; while Winona was selected from Blue Dutch, Minn. No. 175, and has been designated as selection 175-1, or as Plot III 175-1.

These varieties were compared with other resistant selections, under widely different conditions, on both clean and sick soil. On sick soil they showed a higher degree of resistance and greater yielding ability than any variety with which they were compared. The superiority of Winona was particularly marked. They also yielded well on clean soil when comparison was made with the best agronomic types. In addition to being highly resistant to wilt, Chippewa showed quite marked resistance to flax rust caused by *Melampsora lini*. One other selection has demonstrated good yielding ability. This is Selection 91-1, Minn. No. 188, which on clean land seems to out-yield anything with which it has been compared in these tests. On the extremely sick soil upon which the sick-soil yields are based, it averages almost as well as any of the resistant selections except Winona.

While it has been shown that the resistance to wilt is an ordinary genetic character inherent in certain genotypes within recognized flax varieties and that this character is not easily altered by environmental influences, it must be remembered that the reaction of both resistant and susceptible strains of flax is altered greatly by environmental influences. The difference is merely that between the genotypic and phenotypic phases.

The real nature of resistance is not yet known. Whether it is due to rapid growth, to morphological characters, or to a real physiologic incompatibility between the host and the pathogene must be determined by future investigations.

The possibility of the existence of elementary species or biologic forms of *Fusarium lini* also has been investigated by the writer, and, while preliminary results have been obtained, no final conclusions can be drawn at this time altho there is strong circumstantial evidence that there are different forms.

SUMMARY

1. Flax wilt, caused by *Fusarium lini,* has been shown clearly to be a limiting factor in the production of flax. On account of the fact that the pathogene is a soil saprophyte, it often is impossible to grow non-resistant varieties of flax on the same land profitably more than once every ten or twelve years. For this reason flax has been a migratory crop.

2. As *Fusarium lini* lives for a great many years in the soil and lives also in the seed, and as seed treatment is not entirely effective, the only practical method of controlling the disease is the use of resistant varieties.

3. Broekema first suggested the possibility of developing wilt resistant strains of flax. In the United States, Bolley developed several strains which are quite resistant to wilt.

4. The opinion has been prevalent that wilt resistance could be developed in susceptible varieties by association with the disease and that the permanence of this resistance was proportional to the length of time during which the strains had been grown in sick soil.

5. Experiments were made by the writer to obtain definite data on the mechanism by which resistant varieties are obtained, and to ascertain also the degree of permanence of this resistance and the degree to which it could be modified by environmental factors.

6. Individual plant selections were made from several varieties grown on sick soil. Seed was saved from the most resistant plants and from the partially wilted plants. When the progeny of these plants were selfed for two years, the degree of resistance was the same in all, with possibly one exception.

7. Apparently there are different degrees of resistance. Highly resistant plants can be obtained immediately by selection in the field. These plants bred true for resistance.

8. There are no indications that resistance is developed as a result of constant association with the pathogene. Resistant genotypes are present in certain varieties and obtaining resistant strains consists merely in selecting and propagating these genotypes.

9. Reselection or constant association with the disease does not change the degree of resistance of selected genotypes.

10. Not all varieties of flax contain resistant types. The development of resistant varieties, therefore, must be restricted to those varieties in which there are resistant genotypes.

11. The effect of growing flax plants on sick soil is merely to eliminate the susceptible strains and to permit the survival of resistant ones.

12. A wilt-resistant strain does not lose its resistance when grown on clean soil. The natural selection of resistant types, however, ceases to operate.

13. The optimum temperature for the growth of flax is fairly low, while that for the growth of the pathogene is relatively high. Consequently there will be more wilt when flax is grown at high soil temperatures than when it is grown at lower temperatures.

14. Wilt resistance is only relative, and the degree of resistance is therefore modified by environmental conditions.

15. Less wilt usually develops in flax sown early than in that sown later. Susceptible varieties can be grown successfully on sick soil provided the soil temperature is low; resistant varieties may be injured severely by wilt if the soil temperature is high.

16. Two superior wilt-resistant varieties have been developed at the Minnesota station. These are Chippewa, Minn. No. 181, a selection from Primost, Minn. No. 25; and Winona, Minn. No. 182, a selection from Blue Dutch, Minn. No. 175.

17. Extensive yield tests were made with Chippewa and Winona in comparison with other wilt-resistant selections. Winona consistently out-yielded most of the other resistant varieties.

18. Chippewa is not only resistant to wilt but also is moderately resistant to flax rust caused by *Melampsora lini.*

19. Selection 91-1, Minn. No. 188, produces well on sick soil, and yields exceptionally well on clean soil.

20. There is some evidence that there are several physiologic races of *Fusarium lini,* but this has not been demonstrated conclusively.

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PLATE I

Source of Individual Plant Selections Made in 1919

No. 175-1, a wilt-resistant individual plant selection made in 1916. Some of the tagged plants were the most vigorous, and others were partly wilted. The progenies of these were compared to determine the effect of continued selection.

PLATE II

Source of Individual Plant Selections Made in 1919

An unselected variety, No. II-09-15-1, grown on sick soil for the first time. Both vigorous and partly wilted plants were selected

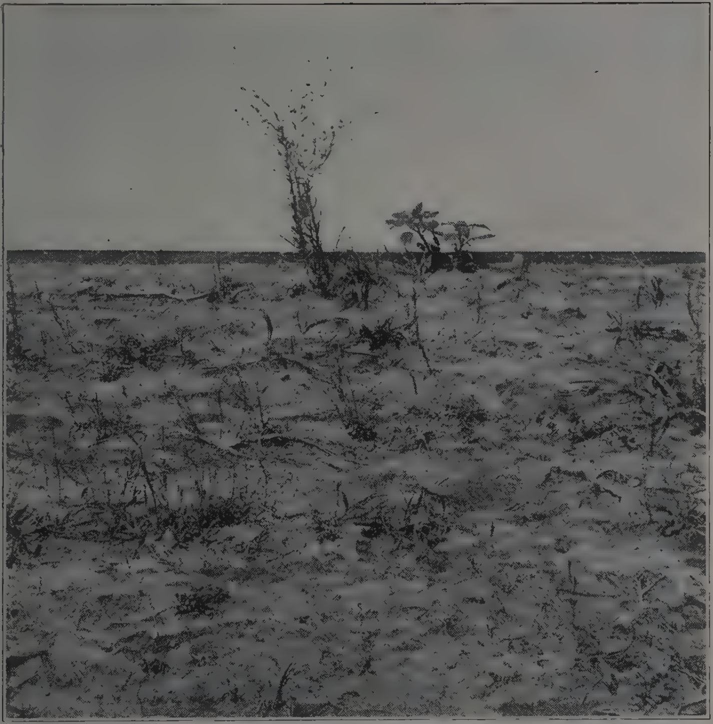

PLATE III

Source of Individual Plant Selections Made in 1919

Minn. No. 25,-M25-5R, the single plant shown in this picture, was the basis of selection. It was highly resistant in the first generation and was not modified by further selection.

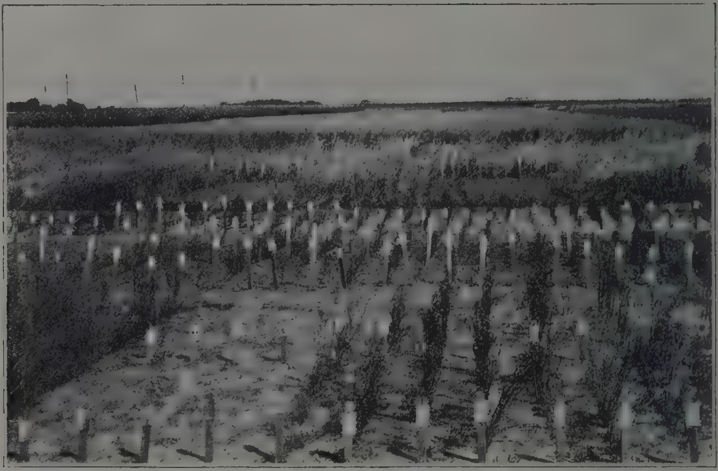

PLATE IV

Effects of Reselection

The progenies of the plant illustrated in Plate III (M25-5R) and of a weak plant (M25-14PR) selected from the same variety (M25) at the same time were selfed in the greenhouse in 1919-20. The seed obtained was planted in 1920 and every plant was saved for testing on sick soil in 1921, as illustrated. The first four rows from the left in the two front series are the progeny of M25-14PR. The remaining rows to the right are the progeny of M25-5R. Reselection was without effect in either case.

PLATE V

Limitations of Selection

Selection C. I. 186 growing on clean soil. This selection was made by C. H. Clark for yield on clean soil at Mandan, North Dakota.

PLATE VI

Limitations of Selection

Selection C. I. 186 growing on sick soil. The only plant that was not killed by wilt proved to be the result of mechanical mixture in the seed. On less sick soil a few plants escaped. Some of them were saved. The progeny wilted as readily as the parent selection. A wilt-resistant selection in all probability could not be selected out of C. I. 186.

PLATE VII

Effect of Clean Soil on Loss of Wilt Resistance

The three rows on the right are selection [illegible] on sick soil after three years' growth on clean soil. This was confirmed by field [illegible]. The three rows at the left show the same selection [illegible] has been grown continuously on sick soil. Note that no loss of resistance appears from growth on clean soil. This was borne out by actual counts of wilted plants and by yield tests.

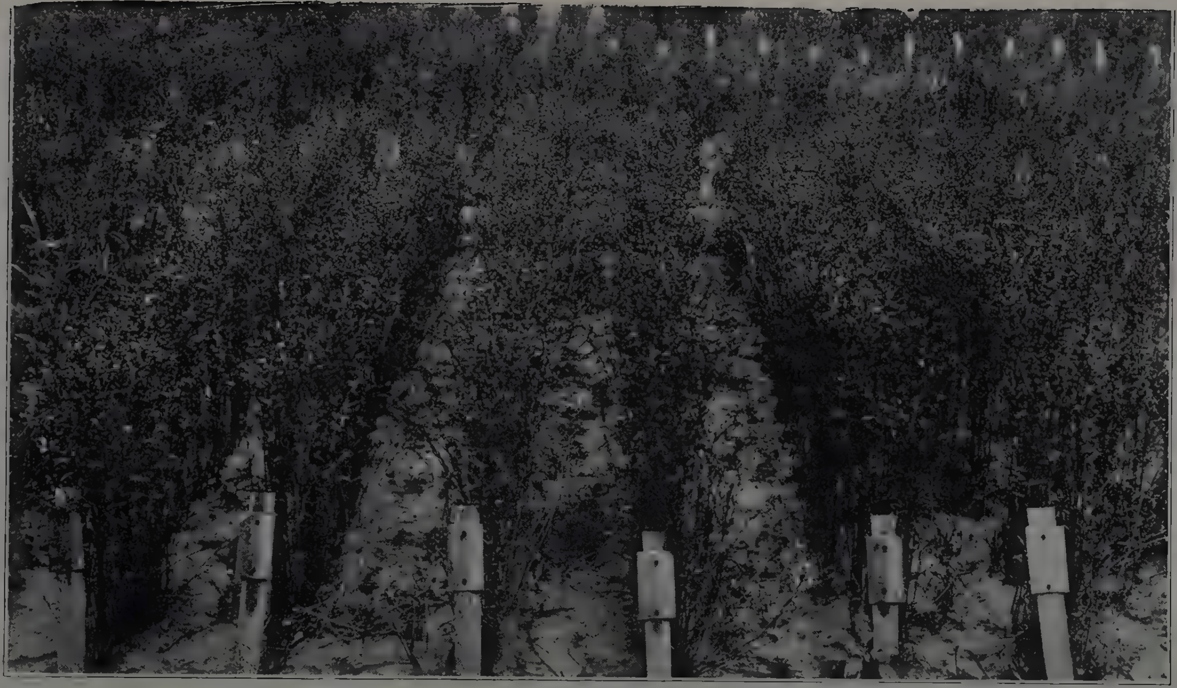

PLATE VIII

Effect of Clean Soil on Loss of Wilt Resistance

The three rows on the right are Selection 175-1 growing on sick soil after three years' growth on clean soil. The three rows on the left show the same selection grown continuously on sick soil. This selection was made in 1916 by the individual plant method. Note that there is no loss of resistance resulting from growth on clean soil, and further that selection has ceased to operate on sick soil. (See Plate IX.)

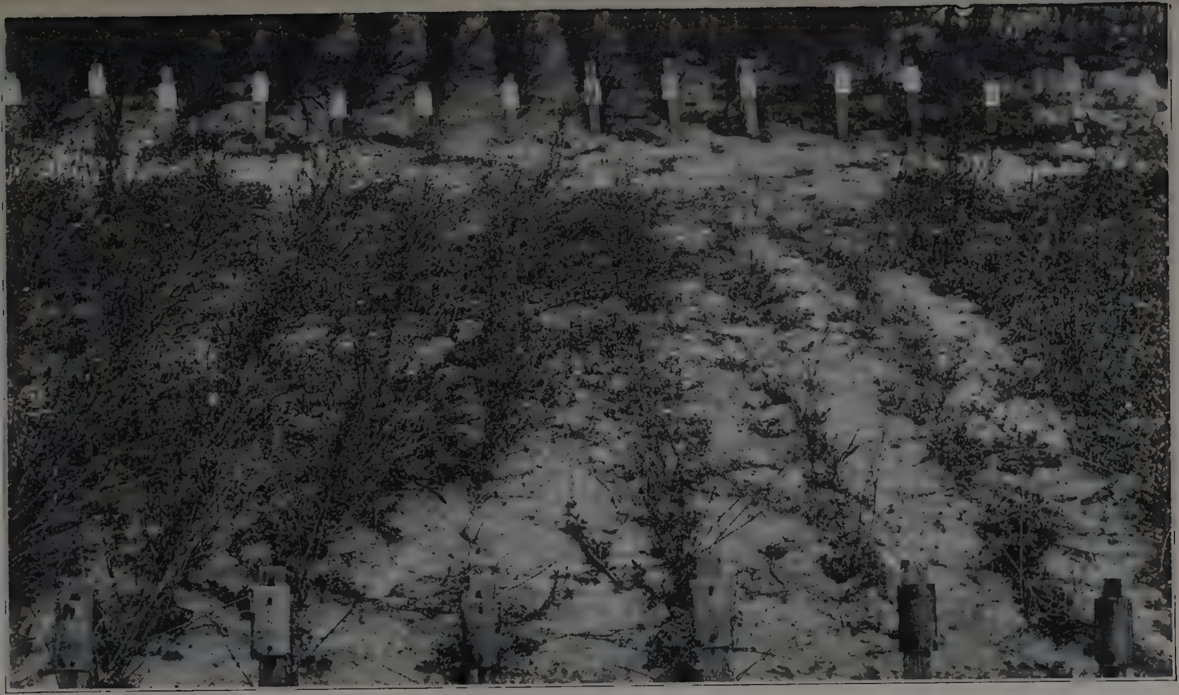

PLATE IX

Effect of Clean Soil on Loss of Wilt Resistance

The three rows on the right are Selection II-09-15-1 growing on sick soil after one year's growth on clean soil preceded by one year's growth on soil that was only partly sick. The three rows on the left show the same selection grown for two years on sick soil.

This apparent loss of resistance is not real, for the three rows on the right are as resistant as the selection was when it was put on clean soil. The three rows on the left from continuous growth on sick soil are better because growth in sick soil has resulted in natural selection.

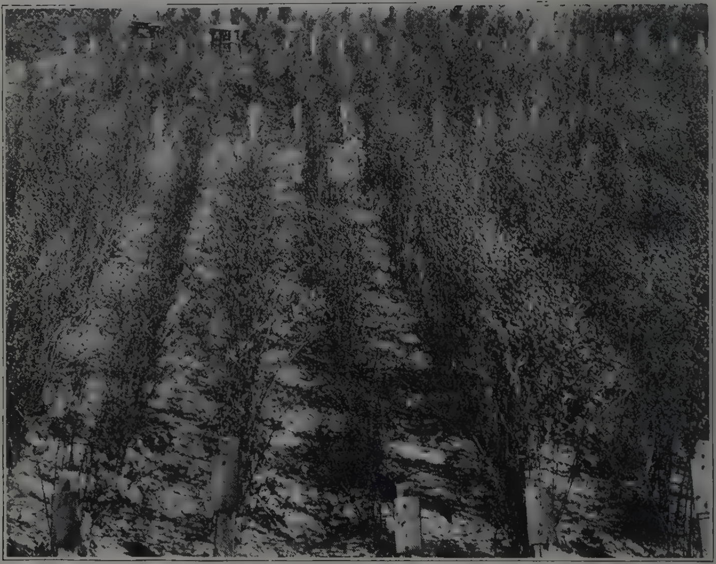

PLATE X

Effect of Time of Planting on Development of Flax Wilt

The three rows on the left show Minn. No. 25, a moderately susceptible non-select variety, planted April 18. On sick soil. Compare with Plates XI, XII, XIII, and XIV.

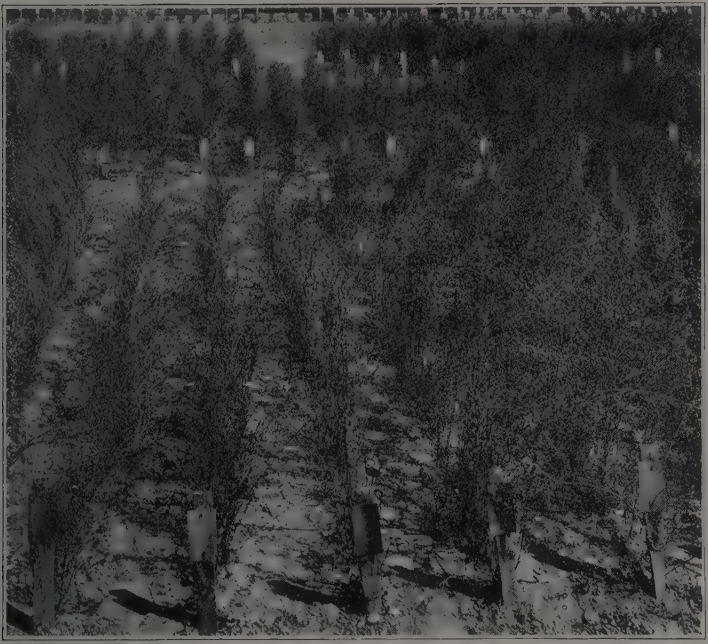

PLATE XI

Effect of Time of Planting on Development of Flax Wilt

The three rows on the left show Minn. No. 25, a moderately susceptible non-select variety, planted May 1. On sick soil. Compare with Plates X, XII, XIII, and XIV.

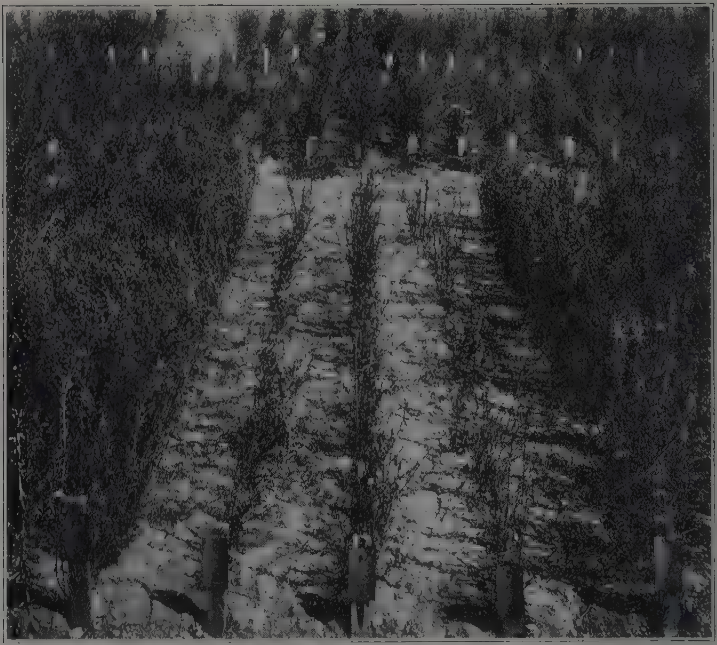

PLATE XII

Effect of Time of Planting on Development of Flax Wilt

The three central rows show Minn. No. 25, a moderately susceptible non-select variety, planted May 15. On sick soil. Compare with Plates X, XI, XIII, and XIV.

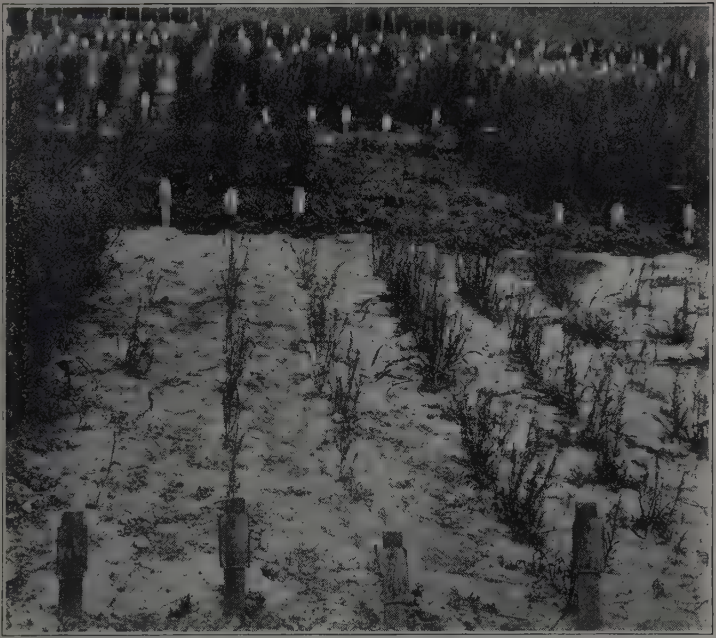

PLATE XIII

Effect of Time of Planting on Development of Flax Wilt

The three rows on the left show Minn. No. 25, a moderately susceptible non-select variety, planted June 1. On the right is Plot IV 25-7, a highly resistant selection when planted early. On sick soil. Compare with Plates X, XI, XII, and XIV.

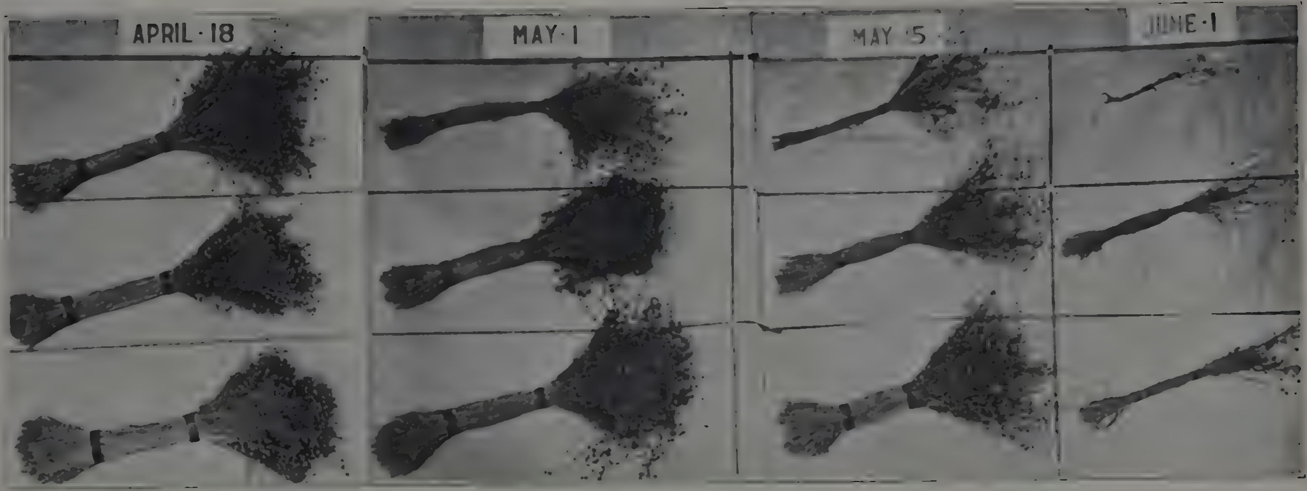

PLATE XIV

Effect of Time of Planting on Development of Flax Wilt

The upper row is Minn. No. 25, a moderately susceptible non-selected variety.
The central row is Chippewa (Selection Plot IV 25-7). This is a highly wilt-resistant variety of flax.
The lower row is Winona (Selection 175-1). This also is a highly wilt-resistant selection.
Note that with early planting a moderately susceptible variety may largely escape wilt, while a highly resistant selection is severely wilted if planted late when soil temperatures are high.

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The University of Minnesota
Agricultural Experiment Station

Reaction of Barley Varieties to Helminthosporium Sativum

PART I. Varietal Resistance

PART II. Inheritance Studies in a Cross Between Lion and Manchuria

By

H. K. Hayes, E. C. Stakman, Fred Griffee, and J. J. Christensen
Division of Agronomy and Farm Management
Division of Plant Pathology and Botany

UNIVERSITY FARM, ST. PAUL

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(Continued on p. 3.)

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* Co-operating with the Bureau of Plant Industry, U. S. Dept. of Agr.

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REACTION OF BARLEY VARIETIES TO HELMINTHOSPORIUM SATIVUM

By H. K. Hayes, E. C. Stakman, Fred Griffee, and J. J. Christensen

PART I. VARIETAL RESISTANCE

INTRODUCTION

Spot blotch disease of barley was mentioned by Pammel (7) in 1909 and was attributed to *Helminthosporium sativum* Pammel, King and Bakke (8) in 1910. Christensen (1) has reviewed previous studies relating to the pathogeneity of *H. sativum* and has pointed out that the parasite is responsible for "leaf spot, root-rot, foot-rot, and seedling blight of wheat, barley, rye, and numerous grasses." Because the organism is so widely distributed and appears to be progressively more destructive, it seems necessary to take steps to control it.

The initial infections under field and greenhouse conditions come from seed or from soil (1). While partial control may be obtained by seed treatment [Louise J. Stakman (10)], good cultural methods, and rotation, the results so far obtained indicate that the use of resistant varieties is by far the most promising means of control.

A preliminary report has been made (6) of the comparative susceptibility of barley varieties and purified hybrids under field conditions at the Minnesota Agricultural Experiment Station. From the results of this study it appeared that there was no close correlation between the mode of reaction of a pure line of barley to *H. sativum* and its botanical or agronomic characters.

The degree of injury caused by *H. sativum* to any variety appeared to be strongly influenced by the environmental conditions under which the crop was produced. In other words, resistance or susceptibility is a relative character and is not absolute. Therefore the disease can best be controlled by combining correct cultural practices with the use of resistant varieties. The purpose of this paper is to present evidence on the comparative resistance of a considerable number of varieties of the four barley species groups. A study also was made of methods of determining the comparative mode of reaction of barley varieties to infections of the causal organism.

The study is a part of co-operative investigations carried on by the sections of plant breeding and of plant pathology which have as their aim the production of disease-resistant varieties of field crops that are also adapted to Minnesota conditions.

MATERIAL AND METHODS

The varieties used in the study were obtained from the material under test in the co-operative barley breeding studies carried on by the plant breeding section of the Minnesota Agricultural Experiment Station and the Office of Cereal Investigations of the United States Department of Agriculture. Most of the varieties used, with the exception of certain hybrids, were obtained originally from the Office of Cereal Investigations, and for this reason are reported under the classification groups as outlined by Harlan (2).

For the field tests of mode of reaction of the varieties, five-foot rows were planted at the rate of 5 grams of seed per row.

The varieties were grown in infested soil and were sprayed at about heading time, at intervals of a day or two, with spore suspensions of *H. sativum.*

The spraying was done between 7 and 8 p.m., from three to five sprayings being made.

Data on the degree of infection were taken when the barley was nearly mature. Separate notes were taken on the degree of infection of heads, culms and nodes, and roots. The terms "heavy," "medium," "light," and "trace," were used to denote degrees of infection; and plus and minus signs further to differentiate the severity of the infection. For more exact comparison, the various degrees of infection were denoted by numerical figures as follows:

trace = 10
light — = 9
light = 8
light + = 7
medium — = 6
medium = 5
medium + = 4
heavy — = 3
heavy = 2
heavy + = 1

These figures allowed a summary of the infection of the separate notes taken on three different parts of the plants, i.e., spike, culm and leaves together, and root, and also aided in determining the degree of correlation between reactions obtained in successive seasons or between the degree of infection of different parts of the plants of the same varieties.

INJURY DUE TO HELMINTHOSPORIUM SATIVUM

Thirty-nine purified smooth-awned strains of barley produced from crosses were grown in replicated rod-row trials in 1921 and 1922. The same strains were grown also for the same years in single five-foot rows and were sprayed with spore suspensions of *H. sativum.*

The rod-row trial plots are grown on series which are under rotation, the cropping plan being as follows: Rye, clover in spring, clover hay, rod-row test of small grains, ear-to-row tests of corn, peas for seed, soybeans, rod-row test of small grains, etc. The legume crops and the cultivation of the corn help to keep the soil in good condition.

The nursery in which the mode of reaction to *H. sativum* was studied was on the same plot each of the three years that the study was carried on.

The calculation of the correlation between average yields as obtained in the rod-row trials, and average reaction to *H. sativum* under artificially induced epidemic conditions, furnishes an opportunity to determine the importance of the pathogene in reducing yields. The smooth-awned hybrids furnished ideal material for this study, as they were obtained for the most part from crosses in which one of the parents was resistant and the other susceptible to attacks of the spot blotch disease. The obtained coefficient (see Table I) +.445±.087 is more than four times the probable error and indicates that susceptibility to *H. sativum* tends to reduce yield. The correlation proves that, under the conditions of the experiment, resistance to *H. sativum* is a character which must be considered by the barley breeder and by the crop producer.

Seventeen 6-rowed strains and varieties of barley were grown for the three-year period, 1919-22, in a replicated rod-row trial. The average yield obtained was correlated with the average reaction to *H. sativum* for 1921-22 (see Table II). The obtained coefficient +.575±.109 is again probably statistically significant and furnishes further evidence regarding the importance of resistance to *H. sativum*.

TABLE I

Correlation in Smooth-Awned Barley Hybrids Between Average Yields for 1921-22, in Bushels per Acre, in Replicated Rod-Row Tests and Average Reaction to *H. sativum* under Artificially Induced Epidemic Conditions

	Average yield					
Average Helminthosporium reaction	42	45	48	51	54	
12	1					1
15	1	3	1		1	6
18	2	1	4	2		9
21		2	8	6	2	18
24		1	2		2	5
	4	7	15	8	5	39

r = .445±.087

TABLE II

CORRELATION IN SIX-ROWED BARLEY STRAINS BETWEEN AVERAGE YIELD, IN BUSHELS PER ACRE, 1920-22, AND AVERAGE REACTION TO *H. sativum* FOR 1921-22 UNDER ARTIFICIALLY INDUCED EPIDEMIC CONDITIONS

Average Helminthosporium reaction	Average yield 30	35	40	45	50	55	
5	1	1					2
10			1	1	1		3
15			2		1		3
20		1	1	3	3		8
25						1	1
	1	2	4	4	5	1	17

r = .575±.109

RESISTANCE OF VARIETIES OF BARLEY TO ATTACKS OF H. SATIVUM UNDER FIELD TEST

A considerable number of varieties of barley have been grown for several years in five-foot rows and an epidemic of spot blotch disease has been produced artificially by spraying the varieties with spore suspensions of *H. Sativum.* The results of the three-year trials are presented in Table III.

In 1920 infection data were taken only on the culm and on the spike and node together. Severity of infection was denoted by average infection. In 1921 and 1922 separate notes were taken upon the degree of infection of spike, foliage, i.e., culm and nodes, and roots, and the results were summarized under the heading "Numerical figure." As was explained under "materials and methods," a high figure, of which 30 is the maximum, denotes very high resistance, while a low figure, of which 3 is the minimum, denotes complete susceptibility.

In the second column of the table the species group is given.

The barley varieties were planted rather late in 1921 and all were much more severely infected than in 1922, when they were planted early in the season. In general, however, varieties that were susceptible one year were likewise susceptible the following year, while those that were resistant one year appeared resistant the following year.

Twelve different pure lines of Manchuria barley were grown in each of the three years. All appeared rather resistant except Manchuria, C 81, which was the most susceptible of the twelve strains in both 1921 and 1922. It seems reasonable to conclude that this strain of Manchuria barley is more susceptible than other strains.

Apparently, therefore, strain differences within the same variety may be of considerable importance.

TABLE III

Reaction of Barley Varieties to *H. Sativum* under Artificially Induced Epidemic Conditions*

Variety name		Species group	Reaction to Helminthosporium											Average numerical figure, 1921 and 1922
			1920	Numerical figure	1921				1922					
					Spike	Foliage	Roots	Num. fig.	Spike	Foliage	Roots	Num. fig.		
		Vulgare												
Manchuria	Minn. 184	H.B.W.R.	L	8	M	M	M+	14	T	L	T+	28		21
	I-16-32	"	L	8	M—	M—	H—	15	T	L—	L—	28		22
	I-16-21	"	M—	6	L+	L+	H—	17	T	L—	T+	29		23
	I-16-29	"	M	5	M—	M—	M+	16	T+	T+	T+	30		23
	I-16-44	"	T+	10	M	M+	M	14	T	T	T+	30		22
	I-16-66	"	L	8	M—	M	H—	14	T	T+	T+	30		22
	I-15-1	"	L	8	L+	M—	M+	17	T	L+	L—	26		22
	I-15-2	"	L	8	M	M	H—	13	T	L	L—	27		20
	C 81	"	L+	7	M+	H—	H—	10	L	M+	L	22		16
	C 96	"	L	8	M—	M	H—	14	T	T	T	30		22
	C 163	"	L+	7	M	M	M	15	L—	L	T+	27		21
	C 168	"	L+	7	M+	M+	M+	12	L—	L	T+	27		20
Bay Brewing×Lion	C 225	"	H	2	H—	H	H—	8	H	H+	H	5		7
Trebi	III-20	"	H	2	M+	H—	M+	11	M	M+	M+	13		12
Trebi	I-16-14	"	M	5	H—	H	H	7	L+	M+	L	19		13
Coast	III-20	"	M+	4	M	H	M—	13	H	H	H	6		10
Winter Club	III-20	"	M—	6	M+	H	M	11	L	H	H	12		12
Beldi	III-20	"	M+	4	M+	H—	M+	11	H	H—	M	10		11
Mariout	III-20	"	H+	1	H	H+	H	5	H+	H	M—	9		7
Mariout	III-15	"	H+	1	H	H	H—	7	H	H	H	6		7
Servian	III-20	"	H	2	M+	H—	H—	10	L—	L	L+	24		17
Servian	I-16-15	"	H—	3	M	M	H—	13	L	M	L	21		17
C. I. 894	I-16-84	"	L	8	M—	M	M	16	L+	T	L+	24		20
Scotch	I-16-45	"	L	8	L	L	M	21	M	M	L+	17		19
Sandrel	I-16-3	"	M+	4	H—	H—	H	8	M	H	M	12		10

TABLE III.—*Continued*

REACTION OF BARLEY VARIETIES TO *H. sativum* UNDER ARTIFICIALLY INDUCED EPIDEMIC CONDITIONS

Variety name		Species group	Reaction to Helminthosporium											Average numerical figure, 1921 and 1922
			1920	Numerical figure	1921				1922				
					Spike	Foliage	Roots	Num. fig.	Spike	Foliage	Roots	Num. fig.	
		Vulgare											
Odessa	I-18-2	H.B.W.R.	H—	3	L	L+	M	20	L	M—	L+	21	21
Luth	C 93	"	L	8	M—	M	M	16	T	T	T	30	23
Sandrel	C 101	"	L+	7	H—	H	M+	9	M	H—	H	10	10
Peruvian	III-20	"	H	2	H—	H—	H—	9	M—	M+	H	12	11
Arequipa	C 267	"	H—	3	†	†	†	3	M—	H	M	13	8
Minsturdi	II-16-47	"	M	5	L+	M	M	17	L	L	L—	25	21
S. Afr. × Manch.	II-16-77	"	M	5	M+	M+	H—	11	L	M	L	21	16
Highland Chief	I-16-31	H.B.W.S.	M—	6	L+	L+	M+	18	T	M+	L+	21	20
Smooth Awn	C 284	"	H	2	L+	M+	M+	15	H—	M+	M+	11	13
Bay Brewing	I-18-3	H.B.B.R.	M—	6	X	H+	H+	3	H—	H+	H	6	5
Gatami	III-20	"	L	8	H	M+	H	8	H—	M+	M+	11	10
Lion	III-20	H.B.B.S.	H	2	H—	M+	H	9	H—	H—	M	11	10
	I-16-13	"	H+	1	H	M+	H—	9	M+	H	M	11	10
	C 270	"	H—	3	H—	H—	H—	9	H—	H	H	7	8
Horsfords	III-20	H.H.W.	M—	6	†	†	†	..	L	L+	L—	24	24
H. v. horsfordianum		H.H.W.	..	..	L+	M	L	20	L	L	T+	26	23
H. v. aethiops		H.H.B.	..	..	M+	M+	H	10	L	M—	L+	21	16
Himalaya	III-20	N.B.W.R.	M+	4	H	H	H	6	H	H—	H	7	7
H. v. coeleste		N.B.W.R.	..	..	M+	M+	M	13	T	L—	L+	26	20
Black Hull-less		N.B.B.R.	..	..	M—	H—	M+	13	T	L—	L+	26	20
Nepal	III-20	N.H.W.	M+	4	X	M+	M	14	T	L	T+	28	21
		Intermedium											
H. i. nudihaxtoni		N.B.W.R.	..	..	L+	H—	H+	11	M	M+	M	14	13
H. i. nudimortoni		N.B.B.R.	..	..	H—	H—	M+	10	L+	M+	L—	20	15
H. i. cornutum		N.H.W.	..	..	X	X	H+	3	T	H+	M+	15	9

---

* Distinct rosetting; symptoms similar to those caused by the so-called take all or rosette disease.

† Discarded.

TABLE III—*Concluded*

REACTION OF BARLEY VARIETIES TO *H. Sativum* UNDER ARTIFICIALLY INDUCED EPIDEMIC CONDITIONS

Variety name		Species group	Reaction to Helminthosporium										Average numerical figure, 1921 and 1922
			1920	Numerical figure	1921				1922				
					Spike	Foliage	Roots	Num. fig.	Spike	Foliage	Roots	Num. fig.	
		Distichon											
Hanna C. I. 906	III-20	H.B.W.R.	..	..	..	..	..	..	T	L	T+	28	28
Hanna	III-20	"	L+	7	L+	M+	M—	17	L+	M	L+	19	18
Hannchen	III-20	"	L	8	M—	M+	M+	14	L+	L+	L	22	18
Boltons	III-20	"	L—	9	M—	M	M	16	T	T	L+	27	22
Svanhals	I-13-21	"	L+	7	L	M	M	18	T	M—	L+	23	21
Boh. × Svanhals	II-16-78	"	L+	7	M	H—	M+	12	T	L	L	26	19
Svansota	II-16-37	"	M—	6	L+	M—	M+	17	T	M	T+	25	21
Chevalier	Minn. 230	"	..	..	..	..	..	..	T	L	L	26	26
Chevalier	III-20	"	L	8	M—	M—	M	17	L	M+	M	17	17
Wh. Smyrna		H B.W.S.	M—	6	M+	M—	H—	13	T	M+	M	19	16
H. d. n. persicum	C.I. 1003	H.B.B.R.	..	..	L	L	M—	22	L	L+	M—	21	22
H. d. n. persicum	S.P.I. 38316	H.B.B.S.	..	..	M	M—	M+	15	L	L+	M—	21	18
Poppenheim		N.B.W R.	..	..	L+	H—	M	15	T	L—	T+	29	22
H. d. nigrinudum		N.B.B.R.	..	..	H—	H	H—	8	L	H	M	15	12
H. d. laxum		N.H.W.	..	..	L+	M+	M	16	L	M	M	18	17
H. d. nigrilaxum		N.H.B.	..	..	H+	H+	H	4	L+	M+	L	19	12
		Deficiens											
H. def. deficiens	C.I. 6684		..	..	M—	M	L+	18	M—	L	L+	21	20
H. def. deficiens		H.B.W.R.	..	..	M	H—	L+	15	L+	M—	L+	20	18
H. def. steudelii		H B.B.R.	..	..	L	H—	M	16	L	M—	L+	21	19
H. def. tridax		H.H.B.	..	..	M—	M+	M	15	L	L+	L—	24	20
H. def. nudideficiens		N.B.W.R.	..	..	M—	H—	H—	12	L+	H—	H	12	12

In the species group column H and N stand for hulled and naked seed; B and H stand for bearded and hooded; B and W stand for black and white; R and S stand for rough and smooth awn. Under Helminthosporium reaction T, L, M, and H stand for trace, light, medium, and heavy infection.

It is not necessary to discuss in detail the behavior of each of the varieties tested, but the reaction of some of the more important commercial varieties will be briefly mentioned.

Trebi, which appears in the table as III-20 and I-16-14, is a pure line resembling Coast. In describing Trebi barley, Harlan and others (4) said "The variety was not especially well adapted to Minnesota. . . . At Aberdeen the variety was in the first rank in the nursery from the beginning. It is especially adapted for irrigated conditions." Trebi has yielded well at University Farm, St. Paul, Minn., but it is very susceptible to attacks of *H. sativum.*

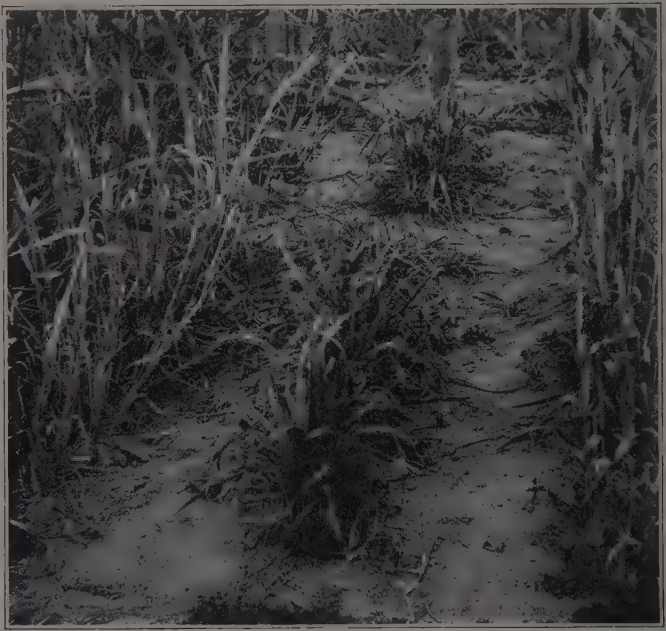

Fig. 1. Varietal Differences in Resistance to *Helminthosporium sativum,* Harvest Time, 1921

At left, Manchuria, Minn. No. 184, resistant; in center, Arequipa, very susceptible; at right, Lion, susceptible.

The new 6-rowed variety, Minsturdi, recently increased by the Minnesota station, appears resistant. It also excels in strength of straw and yield. It is particularly adapted to Southern Minnesota conditions.

In the 6-rowed group, Mariout and Bay Brewing are extremely susceptible to *H. sativum*; while Lion, the smooth-awned, black, 6-rowed variety, is rather susceptible. Gatami, the black, 6-rowed variety, appears susceptible.

The hooded-hulled, white variety, Horsford Beardless, appears resistant.

In the naked, bearded, 6-rowed group, the variety Himalaya (Guy Mayle) appears susceptible, while Black Hull-less appears resistant. Nepal, the naked, hooded, white barley, is resistant.

Three barleys belonging to the *Hordeum intermedium* species group showed considerable susceptibility.

In the *Hordeum distichon* group, Hanna, Hannchen, Svanhals, Boltons, Chevalier, and Svansota appear resistant. These are hulled, bearded, white, rough-awned varieties. Svansota was produced from a cross of an unnamed United States Department of Agriculture variety and Svanhals. It appears especially adapted to the region around Duluth, Minn., and is being distributed for use in this area.

In the *Hordeum deficiens* group both susceptible and resistant varieties have been found.

To determine the accuracy of the estimate of resistance by the reaction as obtained in a single five-foot row, the resistance or susceptibility as obtained for the various years of the study was expressed numerically. Correlation coefficients were computed for the purpose of showing the extent to which resistance or susceptibility was an inherited character. As has been previously noted, environmental conditions widely modify the extent of infection. This was very evident in the variety test carried on at Grand Rapids in 1921. One side of the field stood under water early in the spring and the soil was somewhat over-supplied with moisture late in the season. The barley on this area was much more severely infected with spot blotch than that on the better drained parts of the field.

The notes taken in 1920 were on the basis of the average infection of the varieties, while in 1921 and 1922 separate notes were taken on the infection of spikes, foliage, and roots of each variety. Correlation coefficients have been calculated which express the relation between the infections for successive seasons. If a variety was resistant one season and susceptible the following year the hope of controlling attacks of *H. sativum* by use of resistant varieties would not be very great. The correlation coefficients for the infection in 1920 as compared with 1921, and for 1921 as compared with 1922 are given in Tables IV and V. The coefficients are .497±.073 and .616±.051. These coefficients show that heredity plays an important part in the extent to which a variety is infected. They likewise prove that a test for a single season in a single five-foot row, even when the varieties are artificially sprayed with *H. sativum,* is not sufficient to ascertain whether a variety is resistant or susceptible.

TABLE IV

Correlation Between Degree of Infection of 49 Barley Strains or Varieties for 1920 and 1921

Degree of infection, 1921

Degree of infection, 1920	3	6	9	12	15	18	21	
1		2	1					3
2	1		4		1			6
3	1		1	1			1	4
4		1	2	2				5
5		1		1	1	1		4
6	1			2		3		6
7			2	2	1	2		7
8			1	1	7	2	1	12
9					1			1
10					1			1
	3	4	11	9	12	8	2	49

r = .497 ± .073

TABLE V

Correlation Between the Degree of Infection of 67 Barley Strains or Varieties for 1921 and 1922

Degree of infection, 1922

Degree of infection, 1921	6	9	13	15	18	21	24	27	30	
3	1		1	1	1					4
6	2	1	1							4
9	2	1	5	1		3	1			13
12	1	1	3	1	1	2		5		14
15			1		2	3	2	5	6	19
18					2	2	3	1	1	9
21					1	2		1		4
	6	3	11	3	7	12	6	12	7	67

4 = .616 ± .051

METHODS OF STUDYING MODE OF REACTION TO H. SATIVUM

While the determination of the resistance of susceptibility of varieties of barley was the primary aim of the study, little was known regarding the better means of carrying on the tests. For this reason it seems desirable to present certain facts which show some of the difficulties of the study and which likewise indicate the degree of accuracy with which the facts of resistance or susceptibility may be reached through a single season's trial.

It has been noted that separate notes were taken in 1921 and 1922 on the average infection of spike, foliage, and roots of the varieties in the test. Correlation coefficients have been calculated which denote the behavior of the varieties in two successive years. They are given in Tables VI to VIII inclusive.

TABLE VI

Correlation Between Degree of Spike Infection of 63 Barley Varieties or Strains for 1921 and 1922

Degree of infection, 1921	Degree of infection, 1922 1	2	3	4	5	6	7	8	9	10	
1							1				1
2	1	2	1	1							5
3		1	2		2	1	2	1			9
4		1			1			4	2	3	11
5			1				1	2	1	4	9
6						1	3	2		6	12
7			1		1		1	3		5	11
8					1			3		1	5
	1	4	5	1	5	2	8	15	3	19	63

r = +.488 ± .065

TABLE VII

Correlation Between Degree of Root Infection of 66 Barley Varieties or Strains for 1921 and 1922

Degree of infection, 1921	Degree of infection, 1922 1	2	3	4	5	6	7	8	9	10	
1		1		1	1						3
2		1		1	2	1	1	2			3
3		5			3		1	3	2	3	17
4		1		2	2	1	2	2	2	5	17
5		1			1		6		2	5	15
6		1				1	1				3
7							2				2
8										1	1
		10		4	9	3	13	7	6	14	66

r = .298 ± .076

TABLE VIII

Correlation Between Degree of Foliage Infection of 65 Barley Varieties or Strains for 1921 and 1922

Degree of infection, 1922

Degree of infection, 1921	1	2	3	5	5	6	7	8	9	10	
1	1	1		1							3
2	1	4	2	1							8
3		2	2	5		2		2	2		15
4		1	1	2	3	1	2	2	1	1	14
5					2	1		6		5	14
6				2			2		1	1	6
7				1		1			1		3
8					1			1			2
	2	8	5	12	6	5	4	11	5	7	65

r = +.536±.060

The results show a coefficient of .488±.065 for the correlation between spike infection of the varieties grown in the two years of the test, .298±.076 for root infection, and .536±.060 for foliage infection. Apparently the infection of the foliage is a better criterion of the genetic nature of a variety in relation to resistance or susceptibility than is either spike or root infection.

The correlation obtained for average infection in 1921 in relation to that obtained in 1922, as has been previously noted, was .616±.051. This is slightly larger, altho not significantly so, than the coefficient obtained which shows the relation of spike and foliage infection for the two years.

Correlation coefficients were computed for 1921 and 1922 which show the extent to which an infection note on one part of a plant could be relied on to express the degree of infection which might be expected in another part of a plant of the same variety. The results of this study are presented in Table IX.

The calculated coefficients were larger in all cases for 1922 than for 1921. They were all between 0.7 and 0.8 in 1922, indicating the reliability of the notes taken on the separate parts of plants. In 1921 the coefficients were much smaller, showing that the amount of variability was greater in 1921 than in 1922 or that the experience gained in taking notes in 1921 aided in obtaining more accurate data in 1922. Results seem to justify taking separate notes on the degree of infection of separate parts of a plant as a means of determining whether a variety is resistant or susceptible.

TABLE IX

CORRELATION COEFFICIENTS WHICH EXPRESS THE EXTENT TO WHICH INFECTION IN ONE PART OF A PLANT MAY BE USED TO ESTIMATE THE INFECTION IN ANOTHER PART OF A PLANT OF THE SAME VARIETY

Subject	Relative	No. of strains or varieties	Year of test	Correlation coefficient
Spike infection	Root infection	64	1921	+.562±.048
Spike infection	Foliage infection	63	1921	+.646±.047
Root infection	Foliage infection	65	1921	+.362±.073
Spike infection	Root infection	70	1922	+.713±.040
Spike infection	Foliage infection	70	1922	+.709±.040
Root infection	Foliage infection	70	1922	+.782±.031

In the winter of 1922 an experiment was outlined to determine the possibility of using the greenhouse as a means of isolating varieties resistant to *H. sativum*. Ninety-eight varieties of barley were used. The study was carried in three series:

1. *Check series.*—The soil was steamed for four hours under 15 pounds pressure. The seed was disinfected in silver nitrate for four hours.
2. *Inoculated series.*—The soil and the seed were treated as in the check series. The medium containing the fungus was added to the soil before the seed was planted.
3. *Infected soil series.*—The soil used was obtained from the field in which the study of reaction of barley varieties to *H. sativum* was carried on. The soil was not sterilized and the seed planted was not inoculated.

Three pots of each variety were sown in Series 1 and 3 and four in Series 2. Twenty seeds each were sown in the pots of Series 3 and 25 in those of Series 1 and 2.

Data were taken on percentage of germination, number of seedlings killed, number of stunted seedlings, and degree of foot- and root-rot.

The value of the various notes in relation to the reaction of barley varieties under field trial was determined by correlating the field infection with the greenhouse results. The data are presented in Table X.

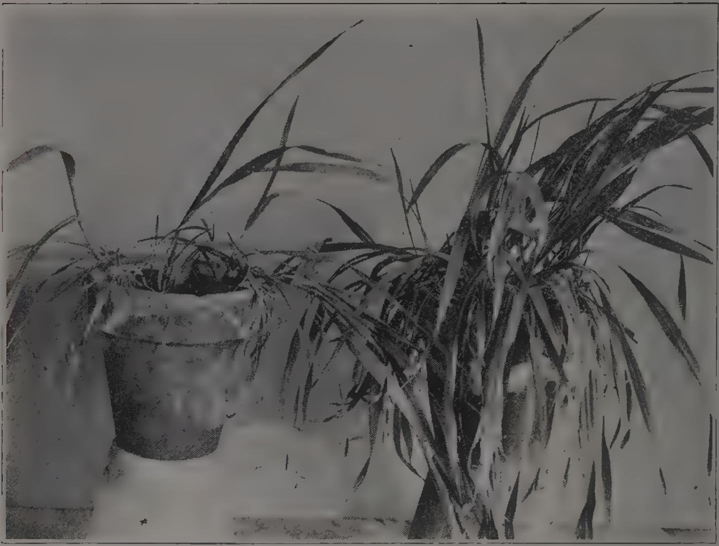

Fig. 2. Varietal Resistance in the Greenhouse, Inoculated Series, 1922-23
At left, Mariout III-15, very susceptible; at right, Manchuria, Minn. No. 184, resistant.

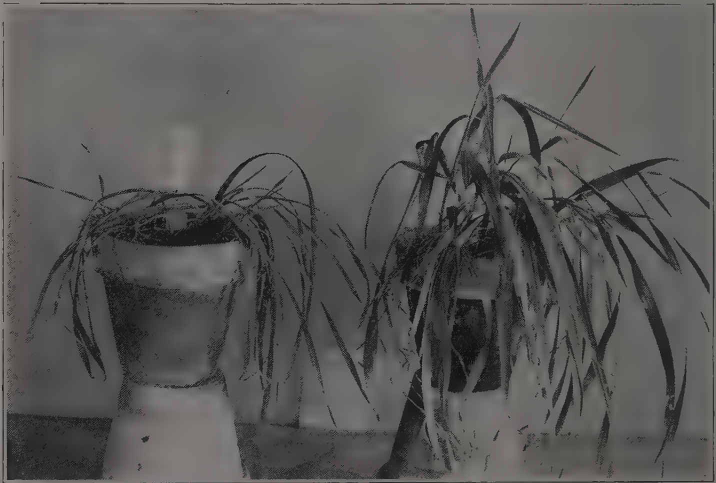

Fig. 3. Varietal Resistance in the Greenhouse, Infected Soil Series, 1922-23
At left, Lion I-16-13, susceptible; at right, Manchuria, Minn. No. 184, resistant.

TABLE X

CORRELATION COEFFICIENTS FOR INFECTION UNDER FIELD CONDITIONS IN RELATION TO INFECTION UNDER GREENHOUSE TEST

Subject	Relative	Correlation coefficient
Average root infection, 1921-22	Root infection, greenhouse. Average, series 1 and 2	+.341±.062
Root infection, 1922	Root infection, greenhouse. Average, series 1 and 2	+.414±.057
Average infection—root, spike, and foliage, 1921-22	Root infection, greenhouse. Average, series 1 and 2	+.373±.061
Average infection—root, spike, and foliage, 1921-22	Percentage seedlings killed, greenhouse. Average, series 1 and 2....	+.129±.067

These results show that the greenhouse trial may be used as an aid to the determination of the mode of reaction under field conditions. The correlations .341±.062, .414±.057, and .373±.061, which express the relation, respectively, between average root infection, 1921-22; root infection, 1922; and average infection of root, spike, and foliage 1921-22, as related to root infection under greenhouse conditions, are not significantly different. They are larger than the correlation for the degree of root infection for 1921 and 1922 which, as has been previously noted, was .298±.076. The correlations for root infection under greenhouse conditions with the average infection under field conditions are somewhat smaller than those for infection in separate years under field conditions when coefficients of .497±.073 and .616±.051 were obtained.

Apparently the number of seedlings killed is not very strongly correlated with the inherited mode of reaction of a variety to *H. sativum.*

COMPARATIVE RESISTANCE OF SMOOTH-AWNED STRAINS AND THEIR PARENTS

As has been noted in the study of reaction of barley varieties to *H. sativum,* the smooth-awned black variety, Lion, is susceptible . The importance of resistance to *H. sativum* was not appreciated when the original hybrids of Lion × Manchuria were made. The smooth-awned strains that were increased were soon found to be undesirable because of their susceptibility to spot blotch disease, and a new series was undertaken of crosses between various rough- and smooth-awned sorts. In all cases the smooth-awned parent used has been shown to be more susceptible to *H. sativum* than was Manchuria. In the F_3 and F_4 generations natural epidemics of *H. sativum* were obtained and there was an opportunity to select resistant types. The thirty-nine purified hybrids, all of which are smooth-awned types, have been

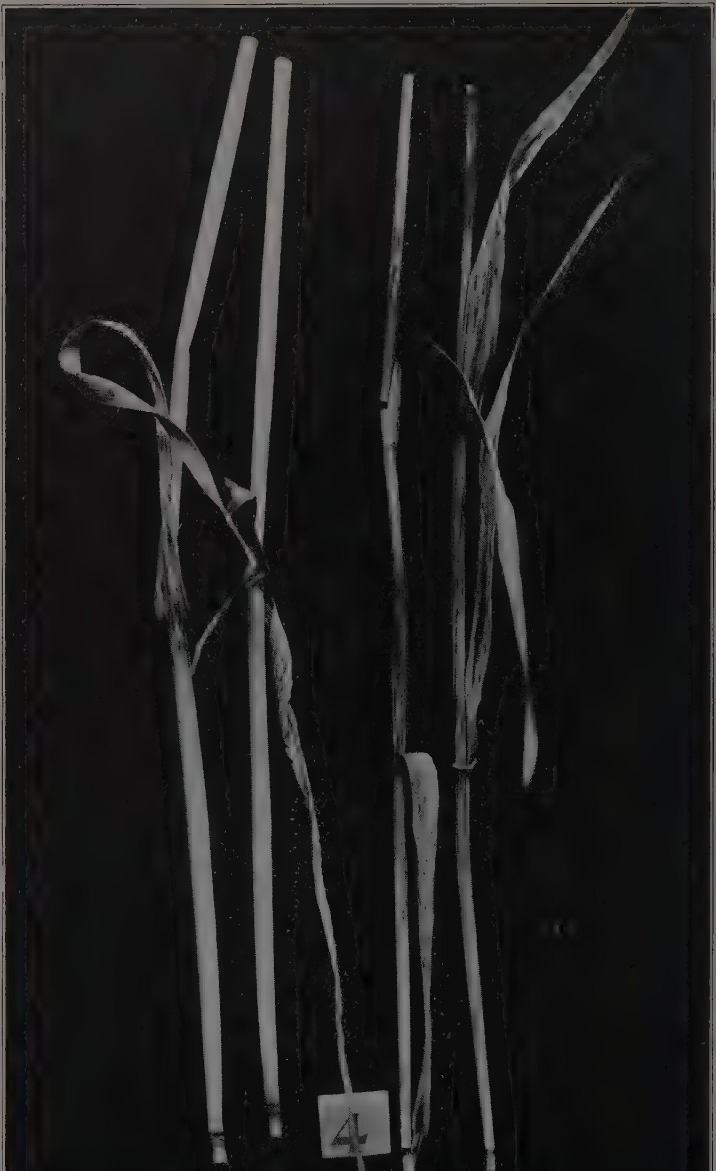

Fig. 4. Relative Reaction of Two Smooth-Awned Hybrids

At left, culms of Manchuria × Smooth-awned selection II-20-10, a resistant desirable type; at right, Arequipa × smooth-awned selection II-21-36, rather susceptible. Disease nursery, 1922.

grown for two years in replicated rod rows in the plant breeding nursery and under artificially induced epidemic conditions in five-foot rows in the plant pathology nursery. As has been pointed out, a correlation of +.445±.087 was found between the yields obtained and the comparative reaction to *H. sativum*. Considering that a large number of susceptible forms were discarded from the trials, the correlation between yield and the reaction to the pathogene appears truly remarkable.

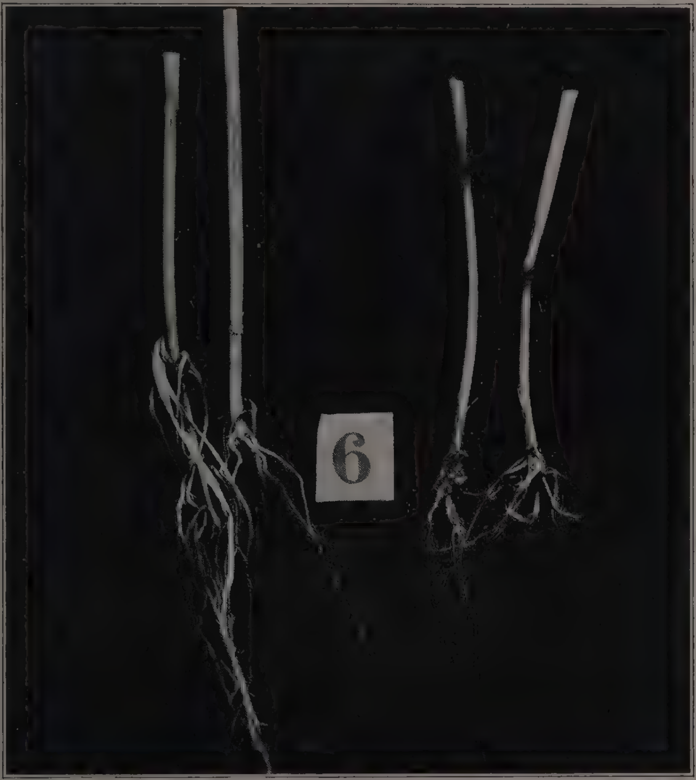

Fig. 5. Relative Reaction of Two Smooth-Awned Hybrids
At left, roots of II-20-10; at right, roots of II-21-36.

The data for average reaction to *H. sativum* and average yield per acre are given in Table XI. Many more than half of the smooth-awned hybrids are as resistant as the resistant Manchuria parents, altho a few strains appear rather susceptible. The smooth-awned parent, Culture 284, is a segregate from a previous Lion-Manchuria cross. It is a white-hulled variety and appears somewhat superior to Lion.

TABLE XI

Reaction to *Helminthosporium sativum* under Infection Conditions, and Yield in Replicated Rod-Row Tests of Smooth-Awned Hybrids and Their Parents

Name		Nursery stock No.	Helminthosporium figure			Yield per acre, bushels		
			1921	1922	Average	1921	1922	Average
Manchuria	Culture 81		10	22	16.0	31.7	56.9	44.2
Manchuria	Culture 96		14	30	22.0	32.0	54.2	43.1
Manchuria	Culture 163		15	27	21.0	30.0	64.2	47.1
Manchuria	Culture 168		12	27	19.5	35.1	71.9	53.5
Manchuria	Culture 274		16	26	21.0	27.3	74.0	50.7
Smooth Awn	Culture 284		15	11	13.0	42.7	53.8	48.3
Manchuria × Smooth Awn	(C96 × C284)	II-20-1	19	24	21.5	34.5	71.7	53.1
Manchuria × Smooth Awn	(")	II-20-2	17	25	21.0	36.7	62.6	50.2
Manchuria × Smooth Awn	(")	II-20-4	17	26	21.5	41.4	54.2	47.8
Manchuria × Smooth Awn	(")	II-21-10	11	16	13.5	33.1	57.0	45.1
Manchuria × Smooth Awn	(")	II-21-11	14	17	15.5	32.5	60.1	46.3
Manchuria × Smooth Awn	(")	II-21-12	17	27	22.0	36.8	61.6	49.2
Manchuria × Smooth Awn	(")	II-21-13	15	25	20.0	29.6	69.8	49.7
Manchuria × Smooth Awn	(C168 × C284)	II-20-18	20	25	22.5	28.5	59.1	44.3
Manchuria × Smooth Awn	(C163 × C284)	II-21-1	16	21	18.5	29.2	65.3	47.3
Manchuria × Smooth Awn	(C81 × C284)	II-21-8	15	23	19.0	37.0	64.6	50.8
Manchuria × Smooth Awn	(C81 × C284)	II-21-9	15	10	12.5	43.4	40.4	41.9
Smooth Awn × Manchuria	(C284 × C274)	II-20-7	17	26	21.5	31.1	65.4	48.3
Smooth Awn × Manchuria	(")	II-20-8	14	28	21.0	33.2	67.0	50.1
Smooth Awn × Manchuria	(")	II-21-14	19	27	23.0	42.9	64.5	53.7
Smooth Awn × Manchuria	(")	II-21-15	15	25	20.0	37.1	65.4	51.3
Smooth Awn × Manchuria	(")	II-21-16	14	26	20.0	34.7	71.5	53.1
Smooth Awn × Manchuria	(")	II-21-17	15	25	20.0	37.1	62.7	49.9
Smooth Awn × Manchuria	(")	II-21-18	16	25	20.5	34.4	64.4	49.4
Smooth Awn × Manchuria	(")	II-21-19	21	25	23.0	36.5	56.6	46.6
Smooth Awn × Manchuria	(")	II-21-20	20	13	16.5	38.1	61.9	50.0
Smooth Awn × Manchuria	(")	II-21-21	15	15	15.0	40.7	46.8	43.8
Smooth Awn × Manchuria	(")	II-21-22	19	23	21.0	33.6	59.7	46.7
Smooth Awn × Manchuria	(")	II-21-24	19	25	22.0	29.5	60.7	45.1
Smooth Awn × Manchuria	(")	II-21-25	14	22	18.0	29.5	54.4	42.0
Smooth Awn × Manchuria	(")	II-21-26	20	25	22.5	33.5	61.6	47.6

TABLE XI—*Concluded*

REACTION TO *Helminthosporium sativum* UNDER INFECTION CONDITIONS, AND YIELD IN REPLICATED ROD-ROW TESTS OF SMOOTH-AWNED HYBRIDS AND THEIR PARENTS

Name		Nursery stock No.	Helminthosporium figure			Yield per acre, bushels		
			1921	1922	Average	1921	1922	Average
Smooth Awn × Manchuria	(C284 × C274)	II-21-27	16	25	20.5	33.5	59.9	46.7
Smooth Awn	Culture 284		15	11	13.0	42.7	53.8	48.3
Luth	Culture 93		16	30	24.0	23.6	66.3	45.0
Smooth Awn × Luth	(C284 × C93)	II-20-9	16	26	21.0	33.2	67.6	50.4
Smooth Awn × Luth	(")	II-20-10*	14	29	21.5	32.4	66.2	49.3
Smooth Awn × Luth	(")	II-21-28	18	27	22.5	35.3	74.9	55.1
Smooth Awn × Luth	(")	II-21-29	19	23	21.0	33.0	64.0	48.5
Arequipa	Culture 267		1	13	7.0	23.1	40.5	31.8
Smooth Awn	Culture 284		15	11	13.0	42.7	53.8	48.3
Arequipa × Smooth Awn	(C267 × C284)	II-20-14	15	24	19.5	35.4	55.6	45.5
Arequipa × Smooth Awn	(")	II-21-34	17	21	19.0	31.9	51.8	41.9
Arequipa × Smooth Awn	(")	II-21-35	14	21	17.5	35.6	58.3	47.0
Arequipa × Smooth Awn	(")	II-21-36	16	13	14.5	34.5	50.2	42.4
Bay Brewing			2	6	4.0	21.5	48.3	34.9
Lion			9	11	10.0	32.6	61.0	46.8
Bay Brewing × Lion		II-20-29	15	12	13.5	39.6	56.9	48.3
Sandrel	Culture 104		9	10	9.5	28.1	59.8	44.0
Smooth Awn	Culture 284		15	11	13.0	42.7	53.8	48.3
Sandrel × Smooth Awn	(C104 × C284)	II-21-30	19	15	17.0	35.7	61.9	48.8
Sandrel × Smooth Awn	(")	II-21-31	14	16	15.0	45.8	60.9	53.4
Sandrel × Smooth Awn	(")	II-21-32	19	16	17.5	33.0	61.6	47.3
Trebi		I-16-14	7	13	10.0	37.0	74.0	55.5
Smooth Awn	Culture 284		15	11	13.0	42.7	53.8	48.3
Trebi × Smooth Awn		II-21-33	19	17	18.0	32.5	59.4	46.0

* This smooth-awned hybrid has been compared with Manchuria, Minn. 184, in field plot trials which have been carried on at both the Central Station and the Substations. It has been approved for distribution under the name Velvet, Minn. No. 447.

Many of the crosses appear very promising and have given yields equal to the better Manchuria selections or superior.

A few of the crosses have not given any hybrids as resistant as the better Manchuria strains. These are worth noting. The crosses between Arequipa, Culture 267, and Smooth-Awn, Culture 284, gave a segregation for reaction to spot blotch disease, but none of the hybrids is as resistant as some strains obtained from other crosses. The Bay Brewing × Lion cross as well as those of Sandrel × Smooth Awn and Trebi × Smooth Awn are all somewhat susceptible. As would be expected, it is very difficult, if not impossible, to obtain resistance from a cross in which both parents are susceptible. This emphasizes the point, which is becoming generally recognized, that the greatest success can be expected from a well organized plant breeding mode of attack in which the parents are selected on the basis of certain desirable characters which they possess.

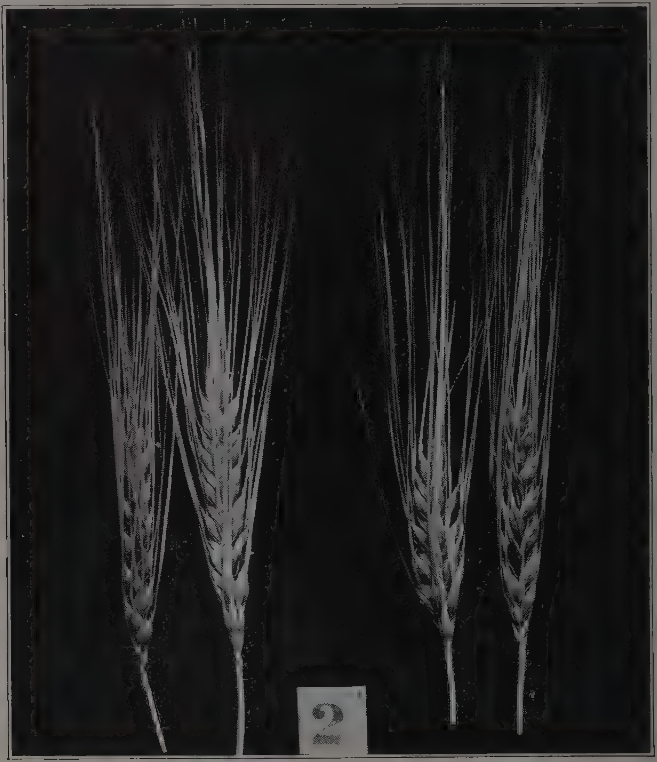

Fig. 6. Relative Reaction of Two Smooth-awned Hybrids

At left, spikes of resistant, smooth-awned hybrid II-26-10; at right, spikes of susceptible smooth-awned hybrid II-21-36.

SUMMARY

1. *Helminthosporium sativum* Pammel, King and Bakke is the cause of a serious disease of barley. The disease appears in various ways and causes culm and foliage spots, foot- and root-rots, and seedling blight, and frequently prevents development of several seeds in each spike.

2. A study of varietal resistance was made by sowing each variety in a five-foot row and spraying the plants at heading time, at intervals of a day or two, with spore suspensions of the causal organism. Yield tests of the same varieties were made in a separate field in replicated rod rows.

3. The importance of the disease is apparent by the correlation between the degree of infection under epidemic conditions (the five-foot row trial) and the yield of the same varieties or strains in replicated rod-row trials. A correlation coefficient between yield and severity of infection for seventeen six-rowed strains was +.575±.109 and for the thirty-nine purified smooth-awned hybrids was .445±.087.

4. Varietal resistance was found to be of utmost importance. In general, varieties which were resistant one year tended to be resistant the following year, while varieties that were susceptible one year tended to be susceptible the following year. Resistance and susceptibility, however, are relative characters and the degree of infection is widely influenced by environmental conditions.

5. Barleys of the Manchuria type proved rather resistant, altho one strain of Manchuria appeared more susceptible each year of the trial than other strains. Mariout and Bay Brewing are extremely susceptible, while Trebi and Lion are rather susceptible. Within the hulled, six-rowed group, therefore, all degrees of resistance and susceptibility were obtained.

6. The new six-rowed variety, Minsturdi, which excels in strength of straw and has been recently introduced to Minnesota farmers, appears resistant.

7. In the naked-bearded, six-rowed group, Himalaya appeared susceptible while Black Hull-less and Nepal were resistant.

8. Nearly all of the more commonly grown two-rowed barleys proved resistant altho some of the two-rowed varieties that were tested proved susceptible.

9. Three varieties belonging to the *Hordeum intermedium* group appeared susceptible, while both resistant and susceptible varieties were grown which belonged to the *Hordeum deficiens* group.

10. Correlation coefficients were calculated which express the correlation of the severity of infection for the separate years of the trial.

Forty-nine varieties or strains were grown in both 1920 and 1921. The calculated coefficient of correlation for the degree of infection for these years was .497±.073. Sixty-seven varieties or strains grown in both 1921 and 1922 gave a coefficient of correlation of .616±.051 for degree of infection for the separate years.

11. Separate notes on the degree of infection of foliage, roots, and spikes were taken and correlation coefficients were calculated which expressed the extent to which infection in one part of a plant may be used to estimate the infection in another part of a plant of the same variety. The calculated coefficients ranged from .362±.073 to .464±.047 in 1921 while all three coefficients were between .7 and .8 in 1922.

12. Seedlings of 98 barley varieties were grown in the greenhouse in soil inoculated with cultures of *H. sativum,* and notes were taken on root infection. The correlation coefficients which express the relation between root infection in the greenhouse and infection in the field were between .3 and .4.

13. Thirty-nine smooth-awned hybrids which appeared homozygous were obtained for the most part from crosses between a smooth-awned susceptible variety and a rough-awned resistant variety. Both resistant and susceptible smooth-awned varieties were obtained.

14. Under the conditions which prevail at University Farm, resistance to *H. sativum* is a character which is of much importance to the plant breeder and the crop producer.

PART II. INHERITANCE STUDIES OF A CROSS BETWEEN LION AND MANCHURIA

Several years ago a cross[1] was made between Lion, a smooth-awned, black barley, and Manchuria, for the purpose of producing a smooth-awned variety of the Manchuria type. When the original cross was made it was not known that Lion was susceptible to *Helminthosporium sativum* P. K. and B. The first smooth-awned varieties produced from the Lion-Manchuria cross were found, after they had been tested for several years, to be susceptible to *H. sativum* and for this reason were discarded altho under some conditions (in the absence of severe *Helminthosporium* injury) these new varieties gave high yields. [See Harlan and Hayes (5), Hayes and Stakman (6)].

Further crosses were made and special attention was paid to *Helminthosporium* resistance as well as to plant type. Varieties are now available which appear as resistant as Manchuria and which in preliminary trials have given high yields. Because of the importance of the smooth-awn habit and of resistance to *H. sativum* it seemed desirable to make a careful study of the mode of inheritance of these characters in the Lion-Manchuria cross. The results will be presented in the following order: (1) Inheritance of awn habit and black vs. white color. (2) Inheritance of reaction to *H. sativum*. (3) Correlation between reaction to *H. sativum* and botanical characters.

INHERITANCE OF AWN HABIT AND BLACK VS. WHITE COLOR

Harlan (3) discussed the introduction of smooth-awned barleys into the United States and pointed out that all smooth-awned barleys are not equally smooth. The fact was emphasized that the teeth which occur on the upper part of the awn of smooth-awned barleys are not particularly objectionable, as the awns are so smooth that they can be pulled across the face in either direction without roughness being apparent except at the tip. By the time the barley spike is mature the tip of the awn frequently breaks off, so that the part on which teeth are borne may be lost before the crop is handled at threshing time.

Vavilov (11) has pointed out that smooth-awned barleys probably were originally obtained by hybridization. This conclusion was reached as a result of certain crosses between rough-awned varieties in which some smooth-awned plants were obtained in F_2. As a rule the progeny of smooth-awned plants bred true for the smooth-awned character. Smooth- and rough-awned barleys in some crosses apparently differed in several inherited factors for awn condition. These factors modified the character, form, and frequency of the teeth produced on rough-awned varieties.

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[1] The crosses were made by the Office of Cereal Investigations, U. S. Dept. of Agr. Subsequent breeding studies have been carried on by the Minnesota Agricultural Experiment Station in co-operation with the Office of Cereal Investigations.

The studies of inheritance reported here are from the F_2 to F_4 generations of crosses between a pure line of Lion, a black, six-rowed, smooth-awned barley; and a pure line of Manchuria, a white, six-rowed, rough-awned variety. From observations made on other smooth-awned strains it was apparent that there was a considerable range in degree of smoothness of the awns in the segregating generations. Accordingly, the F_2 generation of the Lion-Manchuria cross was classified into three groups, rough, intermediate smooth, and smooth.

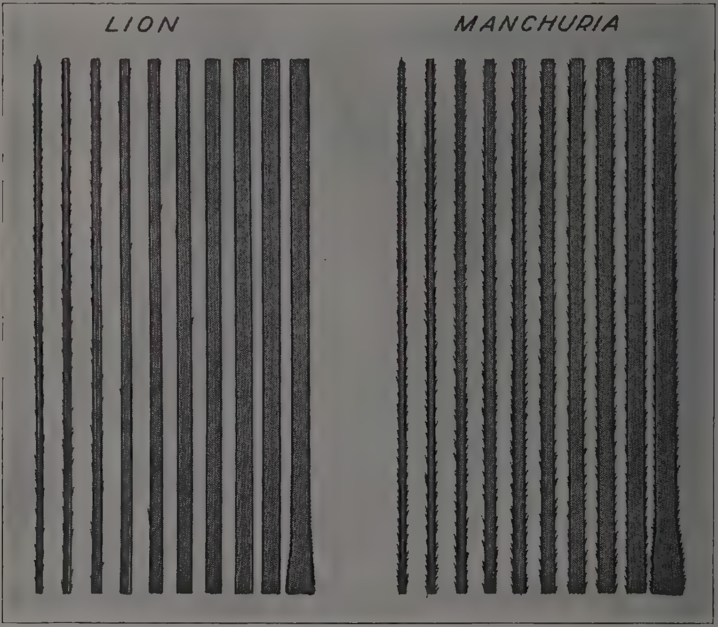

Fig. 7. Lengthwise Section of Average Awn of Lion and Manchuria Barleys Enlarged approximately eight times. (Drawing by George)

The rough group, similar to Manchuria, produced teeth on the entire length of the awn. All smooth-awned barleys that have been grown at the Minnesota Experiment Station have some teeth on the tip of the awn and also have teeth at the extreme lower base of the awn, altho in the smooth-awned barleys there are teeth on the base for only a short distance. A comparison of the relative size and number of teeth on Lion and Manchuria barleys may be seen in Figure 7.

In discussing the relative smoothness of the awns of various smooth-awned hybrids the teeth at the awn base will be disregarded.

The intermediate group produced teeth on approximately the upper half of the awn altho there was some part of the lower half of the awn upon which no teeth were apparent; while the smooth group produced teeth on approximately the upper third of the awn only.

The F_2 generation grown in 1918 from nine separate F_1 plants is classified in Table XII for color of spike and condition of awn. Of 315 plants, 225 were rough-awned and 90 were smooth-awned. The deviation from expectation on the basis of a single main factor difference between rough and smooth is 11.25, while the probable error on the basis of 315 individuals is 5.18.[2] A deviation as great as this might be expected to occur about once in every 7.28 trials. There were 225 black and 90 white, the same ratio as was obtained for rough vs. smooth awns.

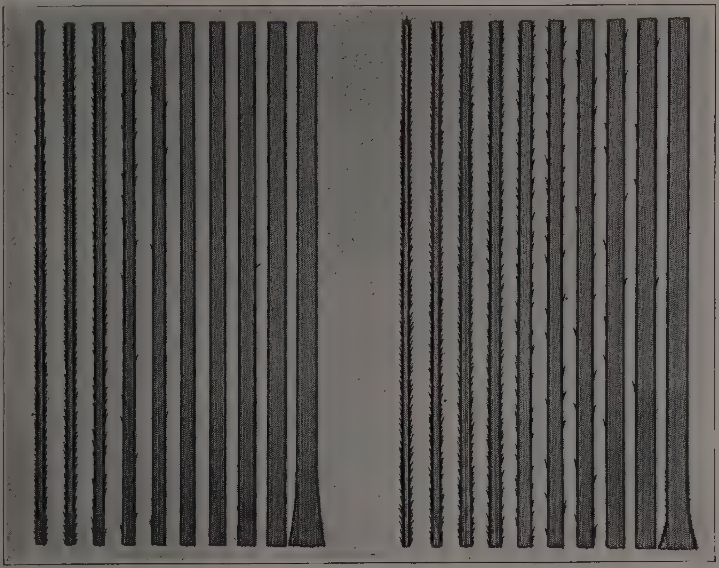

Fig. 8. Lengthwise Section of Average Awn of Two Families of Lion × Manchuria Barley
At left, average awn of a plant of the smooth-awned hybrid family, Culture No. 205; at right, average awn of a plant of the intermediate smooth-awned hybrid family, Culture No. 266. Enlarged approximately eight times. (Drawing by George.)

[2] Probable errors of Mendelian ratios were obtained from tables of probable errors from the Department of Plant Breeding, Cornell University.

TABLE XII

F_2 GENERATION OF LION × MANCHURIA CLASSIFIED FOR COLOR AND CONDITION OF AWN

F_2 plant No.	"Rough"		"Interm. smooth" Sl. rough		"Smooth" V. Sl. rough	
	Black	White	Black	White	Black	White
52	25	9	5	2	2	1
54	9	8	8	1	4	1
49	13	9	4	3	3	1
50	19	3	12	1	5	1
51	19	10	2	4	1	1
53	17	5	3	5	2	0
56A	26	9	1	0	2	2
56	11	6	3	2	2	0
55	22	5	2	0	3	1
Total	161	64	40	18	24	8
	225		58		32	

There was no apparent linkage in inheritance of the allelomorphic pairs for rough vs. smooth awn and black vs. white color, as may be noted by an examination of the results obtained in F_2.

	Black rough	Black smooth	White rough	White smooth	Total
Observed	161	64	64	26	315
Calculated	177	59	59	20	315
Difference	16	5	5	6	0
	$X^2 = 4.08$		$P = .2543$		

Further proof that black and white are dependent for their expression upon a main factor difference was obtained from the F_3 generation. Of a total of 62 F_3 families planted from black F_2 plants selected at random, 18 were homozygous for black an 44 produced both black and white plants.

In order to make a more exact study of the mode of inheritance of the smooth vs. rough awn habit, the various plants were classified by determining what part of the total length of the awn produced teeth rather regularly.

An awn of average length was taken from the center of the main spike of each plant and was carefully examined under the binocular. The distance on the tip of the awn upon which teeth were regularly borne was measured. The total length of the awn was divided by the length of the tip upon which teeth were found. The result obtained was called the awn index; the larger the index the smoother the awn, and vice versa.

Plants of the Lion parent with different indices were selected and the progeny were compared for awn index value. (See Table XIII.)

TABLE XIII

Inheritance Studies of Awn Index Values with the Lion Parent

Index of parent plant	Year grown	Awn index classes, progeny										
		2.5	2.8	3.1	3.4	3.7	4.0	4.3	4.6	4.9	5.2	5.5
	1921	1	14	21	21	18	4	4	1	1		
3.1	1922		4	2	1	1						
3.0	"	1	2	6	3	1						
4.0	"	1		4	1		1				1	
2.5	"	1		2	1	2	1					
3.4	"	1	2	5	3	2	1					
3.3	"		4	6	2	1						
3.4	"	1	5	2	2							
4.0	"	1		8	3	1	1					
3.1	"	1	1	2	2		1	1				1
3.0	"	3	3	1	2	2						
2.7	"	1	2	1			1					
3.2	"			2	1	1						
2.8	"	2	3	4	2	2	1					
2.8	"	3	2	3	1	2		1	1			
2.7	"	1	2	2	2	4						
Total	1922	17	30	50	26	19	7	2	1	0	1	1

The results obtained for the Lion parent indicate a considerable range of variability for the awn index. There is, however, little indication that the variations are heritable, for little or no relation is apparent between the index of the parent plants and the index of the progeny. Such fluctuations as appear on individual plants of the Lion parent are apparently not heritable.

A careful examination was made in 1921 of the spikes of nearly three hundred F_2 plants of the Lion-Manchuria cross for degree of smoothness of awn. The results are compared with the parents, Manchuria and Lion, and are also compared with various F_3 families which were grown the same season from F_2 plants whose awn indices were known. This material was likewise tested for reaction to *H. sativum*. A summary of the results for awn indices is given in Table XIV.

There were 203 rough-awned F_2 plants and 85 smooth-awned plants of various degrees of smoothness. Of these, 39 had teeth for a greater distance on the awn than is usual on the Lion parent. On the basis that there is a single main factor difference between rough and smooth awn, the expected ratio for 288 plants would be 216:72. The deviation from expectation is 13 and the probable error in numbers for 288 plants on a 3:1 basis is 4.96. The deviation divided by the probable error is 2.6. A deviation as great as this might be expected to occur once in every 12.58 trials.

TABLE XIV

INHERITANCE OF SMOOTH VERSUS ROUGH AWN HABIT IN F_2 AND F_3 OF THE CROSS BETWEEN LION AND MANCHURIA

Variety	Culture No.	Awn index of parent plant	No. of families	Awn index classes of progeny							
				1.0	1.3	1.9	2.8	3.7	4.6	5.5	6.4
Manchuria			6	66							
Lion			6				97	62	3	2	
Man. × Lion F_2			7	23	1	38	39	7			
Man. × Lion F_3	166	2.5			1	15					
"	170	2.1			1	10					
"	182	1.8				16					
"	252	1.6				16					
"	266	1.0			3	8					
Total			5		5	65					
Man. × Lion F_3	171	1.8				10	6				
"	174	2.2				9	9				
"	175	2.0				3	1				
"	172	2.1				11	2				
"	207	1.9			1	12	2				
"	216	2.2			1	12	1				
"	236	2.3				8	12				
"	237	2.3				10	7				
"	238	1.8				18	6				
"	240	2.1				7	7				
"	181	2.1				10	5				
"	217	2.0				14	6				
"	271	2.0				6	14				
Total			13		2	130	78				
Man. × Lion F_3	169	2.0				7	5	2			
"	173	2.1				9	3	1			
"	176	2.2				9	4	1			
"	177	2.2				3	2	5	1		
"	215	2.2				5	9	1			
"	218	1.8				3	4	6	2		
"	249	1.8			1	7	2	2	1		
"	253	1.6			2	2	2	2			
"	270	2.0			1	10	1	2	1		
"	272	1.9				9	9	4			
"	273	2.1				5	5	2			
"	282	1.8				8	6	1			
Total			12		4	77	52	29	5		
Man. × Lion F_3	206	2.2						13	2	1	1
"	208	2.4					3	5	6	1	
Total			2				3	18	8	2	1
Man. × Lion F_3	165	3.3					7	8			
"	205	3.8						9	8	4	
"	239	3.4					2	6	5	2	
"	248	2.6					2	5	2		
"	281	2.8					4	4	2		
Total			5				15	32	17	6	

TABLE XIV—*Concluded*

INHERITANCE OF SMOOTH VERSUS ROUGH AWN HABIT IN F_2 AND F_3 OF THE CROSS BETWEEN LION AND MANCHURIA

Variety	Culture No.	Awn index of parent plant	No. of families	Awn index classes of progeny							
				1.0	1.3	1.9	2.8	3.7	4.6	5.5	6.4
Man. × Lion F_3	250	2.7				7	5	2	2		
“	280	2.9				1	8	9	1	1	
Total			2			8	13	11	3	1	
Man. × Lion F_3	Total	1.0	21	338							
“	185	1.0		13		2	1				
“	187	1.0		11		4	5				
“	192	1.0		2		3					
“	194	1.0		19		1	3				
“	197	1.0		7		2					
“	198	1.0		8		1					
“	220	1.0		16		1	1				
“	227	1.0		9		1	1				
“	228	1.0		14		2	1				
“	231	1.0		12		2	2				
“	232	1.0		15			3				
“	241	1.0		14		4	1				
“	244	1.0		21		3	1				
“	247	1.0		11		3					
“	254	1.0		4		1					
“	258	1.0		14		7	1				
“	260	1.0		12		1					
“	261	1.0		12		1	1				
“	262	1.0		7		4	1				
Total			19	221		43	22				
Man. × Lion F_3	219	1.0		12		2	2	2			
“	224	1.0		13		1		1			
“	234	1.0		9		1	5	1			
“	235	1.0		15		2	3	1			
“	245	1.0		17		2	2	1			
“	246	1.0		5		1		1			
“	255	1.0		11		3	3	2			
“	257	1.0		9		2	2	2			
Total			8	91		14	17	11			
Man. × Lion F_3	191	1.0		16			2	2			
“	193	1.0		14				3	2		
“	202	1.0		9			5	1			
“	213	1.0		5			3				
“	214	1.0		12			2	2	1		
“	223	1.0		13				1			
“	225	1.0		11			2	2			
“	229	1.0		16				1	1		
“	259	1.0		13			2	4	2		
“	265	1.0		19				1	2		
“	268	1.0		10			4	3	3		1
“	277	1.0		13			3	4			
“	278	1.0		9			3	3			
Total			13	160			26	27	11		1

A total of 63 F_3 lines from rough-awned F_2 plants was grown. Of this number, 21 bred true for the rough-awn habit while 42 gave both rough- and smooth-awned plants. These results give further proof that a single main factor differentiates rough- and smooth-awned types. The F_3 families which produced both rough- and smooth-awned plants were placed in three different groups on the basis of the degree of smoothness of the smooth-awned segregates. In one group of 19 families the awn index of the smooth-awned plants was low. In another group of 13 families the smooth-awned plants were all of an awn index similar to that of the smooth-awned parent, Lion; while the third group contained smooth-awned plants of both a high and a low awn index. The numbers of individuals were small in these F_3 lines. The F_3 families which produced both grades of smooth-awned individuals are without doubt genotypically of the nature indicated. The number of individuals in the F_3 families in which rough-awned plants and smooth-awned plants obtained were in either the low index group or in the high index group, was too small to prove conclusively that the particular family was genotypically capable of producing only one class of smooth-awned plants.

In the 63 families which segregated giving both smooth-awned and rough-awned plants, there were 644 plants, of which 172 were smooth-awned. On a 3:1 basis, 161 smooth-awned plants should be expected. The deviation from expectation is 11 and the probable error for a 3:1 ratio on the basis of 644 individuals is 7.41.

All smooth-awned F_2 plants bred true for the smooth-awned condition in F_3. The F_3 families were, however, of different apparent type, for some produced only plants of low-awn indices, others produced only plants of high-awn indices, while still others produced some smooth-awned plants of both low- and high-awn indices.

Several lines from different F_3 types were tested by growing F_4 progeny. (See Table XV.)

From the F_3 group with the lowest average index, two lines were selected, Nos. 166 and 266. Both bred comparatively true to the low index habit in F_4, altho family 266 produced a somewhat lower average index than family 166.

From the near intermediate smooth group 6 lines were tested in F_4. Of these, 2 gave rather clear indication of segregation while 4 bred comparatively true. Of the 5 segregating lines, 4 gave evidence in F_4 that showed that these 4 lines were not homozygous. From the fifth line, F_3 plants with a high awn index only were selected for planting in F_4. The two lines tested bred true for the high index character. The 4 F_3 families with as high average index as Lion, bred true for a high index in F_4.

TABLE XV

F$_4$ Breeding Behavior in Relation to F$_3$ Group for Awn Index

Parent plant	Awn index of parent plant	Group of parent plant	Gen.	Awn index classes of progeny						
				1.3	1.9	2.8	3.7	4.6	5.5	6.4
166	2.5	Int. smooth	3		15					
166-3	2.0		4	1	10	5				
166-4	2.0		4		5	2				
166-13	1.7		4		14	2				
266	1.0	Int. smooth	3	3	8					
266-9	1.6		4	3	16					
266-12	1.8		4	1	8					
266-5	1.6		4	1	7					
174		Near Int. smooth	3		9	9				
174-6	2.6		4		1	7	1			
174-10	2.0		4			5				
181	2.1	Near Int. smooth	3		10	5				
181-14	2.3		4	3	12					
181-3	2.0		4		4	5				
181-10	2.1		4	2	18					
207	1.9	Near Int. smooth	3	1	12	2				
207-12	2.6		4	1	11					
207-14	1.5		4	1	19					
207-3	1.5		4	3	19					
271	2.0	Near Int. smooth	3		6	14				
271-12			4		1	5	5	1		
271-5			4		2	9	3	3		
236	2 3	Near Int. smooth	3		8	12				
236-1	2.0		4		16	6	1			
236-11	2.9		4		20	1				
237	2.3	Near Int. smooth	3		10	7				
237-2	3.1		4		2	6	3	1		
237-5	2.5		4		13	8	1			
177	2.2	Segregating	3		3	2	5	1		
177-1	4.5		4			2	2			
177-4	2.3		4	1	5	2				
218	1.8	Segregating	3		3	4	6	2		
218-2	3.3		4		15	4	1			
218-3	2.8		4		3	5	12	4		1
218-4	3.8		4			1	7	10		2
218-5	4.1		4			13	6	1	4	
218-12	4.0		4		9	8	4			
218-15	3.4		4		2	12	5	1		
249	1.8	Segregating	3	1	7	2	2	1		
249-3	1.4		4		10	3	2			
249-7	1.8		4	1	15					
249-10	4.2		4			3	12			
253	1.6	Segregating	3	2	2	2	2			
253-1	3.7		4			9	6	3		
253-3	1.4		4		4	1				
253-7	2.3		4		17	2				

TABLE XV—*Concluded*

F$_4$ Breeding Behavior in Relation to F$_2$ Group for Awn Index

Parent plant	Awn index of parent plant	Group of parent plant	Gen.	Awn index classes of progeny						
				1.3	1.9	2.8	3.7	4.6	5.5	6.4
250	2.7	Segregating	3		7	5	2	1		
250-1	3.3		4				5	2	4	4
250-17	3.8		4			1	7	8		4
206	2.2	Smooth	3				13	2	1	1
206-6	4.1		4			6	4	3	3	3
205	3.8	Smooth	3				9	8	4	
205-2	4.0		4			1	11	1		
205-3	4.0		4			4	11	4	1	
205-13	4.1		4			2	7	4	2	2
248	2.6	Smooth	3			2	5	2		
248-5	3.2		4			3	5	5	2	
248-6	4.0		4				9	1		
248-4	2.8		4			3	5			
239	3.4	Smooth	3			2	6	5	2	
239-8			4			2	5	1	1	1
239-9			4				3	2		
239-15			4			2	6	5	5	2
239-2	4.4		4			5	16	1	1	
239-12	3.3		4			2	9	7	1	
239-13	4.7		4			5	13	3	1	1
239-16	4.6		4			6	11	5	1	
239-17	3.2		4			5	9	5	2	

These results prove that the degree of smoothness of the awn is an inherited character and apparently dependent on genetic factors. The simplest explanation is that there is one main factor which differentiates smooth- and rough-awned types and that modifying factors determine the degree of smoothness of the awns of the smooth-awned plants. This seems a better explanation than the view of a variable factor, for types breed true in F$_3$ and F$_4$ for different degrees of smoothness.

INHERITANCE OF REACTION TO H. SATIVUM

The F$_3$ and F$_4$ families, of which from 10 to 25 plants each were grown, were inoculated about heading time by spraying with a spore suspension of *Helminthosporium sativum*. About harvest time a separate note was taken on each plant on the degree of infection of spike, culm and leaves together, and root. The notes were taken as heavy, medium, light, and trace, plus and minus signs being used to denote deviation from the class centers. In order to average the results the following numerical figures were used:

trace = 10
light — = 9
light = 8
light + = 7

medium — = 6
medium = 5
medium + = 4

heavy — = 3
heavy = 2
heavy + = 1

By averaging the results for the three groups a numerical index of degree of infection was obtained. The least infection obtainable was represented by trace, or 30, while the heaviest obtainable infection would be heavy + or 3, i.e., heavy + on spike, culm and leaves, and root.

At frequent intervals, approximately every tenth to twentieth row, the parents were planted.

The difficulty of a study of this kind is that environmental conditions so widely influence the degree of infection. In a single resistant variety, such as Manchuria, plants may be found which are very heavily infected, altho the other plants in the population may escape serious injury. Similarly, a susceptible variety, such as Lion, may produce an occasional plant which is only moderately infected. These facts may be illustrated by the variations obtained in 1921 from the parental rows.

TABLE XVI

Variation in Infection of Rows of Pure Lines of Manchuria and Lion Barleys

Variety	Row No.	Range of infection numerically expressed	Mean infection
Lion	167	6 – 8	6.9
Manchuria	168	12 – 22	17.0
Lion	178	6 – 13	11.1
Manchuria	179	14 – 18	15.7
Lion	189	7 – 15	11.5
Manchuria	190	12 – 23	18.2
Lion	200	6 – 13	9.6
Manchuria	201	8 – 16	13.1
Lion	221	7 – 14	11.2
Manchuria	222	9 – 20	15.3
Lion	242	11 – 17	14.2
Manchuria	243	11 – 23	17.9
Lion	263	10 – 15	12.3
Manchuria	264	10 – 18	14.1
Lion	284	9 – 17	13.3
Manchuria	285	10 – 23	17.4
Lion	305	5 – 12	8.3
Manchuria	306	6 – 26	16.8

In order to discover whether the difference in reaction of individual plants with a pure line such as Lion or Manchuria was heritable, several plants of both a high and a low infection were selected and their progeny grown the following year. Within each pure line the progeny from the plants which were severely infected in 1921 were no more severely injured in 1922 than the progeny from the plants which in 1921 were only slightly injured. The following will serve as typical illustrations:

Variety	Parent plant	Average infection of parent plant	Average infection of progeny
Manchuria	168–11	14	26.5
Manchuria	168–7	22	23.8
Manchuria	179–7	14	27.8
Manchuria	179–5	18	26.5
Manchuria	264–10	11	24.8
Manchuria	264–9	18	25.3
Lion	189–1	7	19.2
Lion	189–15	16	18.4
Lion	200–4	7	15.6
Lion	200–1	13	13.5
Lion	263–4	10	13.1
Lion	263–12	14	13.4

The variability which was obtained from the various cultures of the parents may be noted from the data given in Table XVII. In 1921 the barley plots were planted much later than in 1922. Both varieties were much more severely infected in 1921 than in 1922. In fact the resistant variety, Manchuria, was nearly as severely infected in 1921 as the susceptible variety, Lion, was in 1922. There was, however, a very significant difference in both years between the average infection of the two varieties.

The standard deviations for the susceptible variety, Lion, were larger in both years than for Manchuria, altho the differences are not statistically very significant.

The probable error of a single determination, i.e., the use of a single row for Lion, in 1922, would be 2.46×.6745, or 1.66. This shows that rather large deviations may be expected.

The means of 124 F_3 lines of the Manchuria-Lion cross are given also in Table XVII. While the means cover as wide a range of variability as the combined range of Lion and Manchuria, the calculated standard deviation is only .86±.40 greater than for Lion, which is not statistically very significant.

As has been mentioned, Lion and Manchuria were grown every tenth to twentieth row. After comparing the means obtained for the parent lines with those obtained for the hybrids, certain hybrid families were selected which appeared to be either as susceptible as Lion or as resistant as Manchuria. Within each apparently susceptible F_3 line two of the most resistant plants and one susceptible plant were selected, and within each apparently resistant family two of the most susceptible plants and one resistant plant were selected. An F_4 culture was grown in 1923 from each of these selected plants.

Average results are given in Table XVIII for the various rows of the parents and crosses.

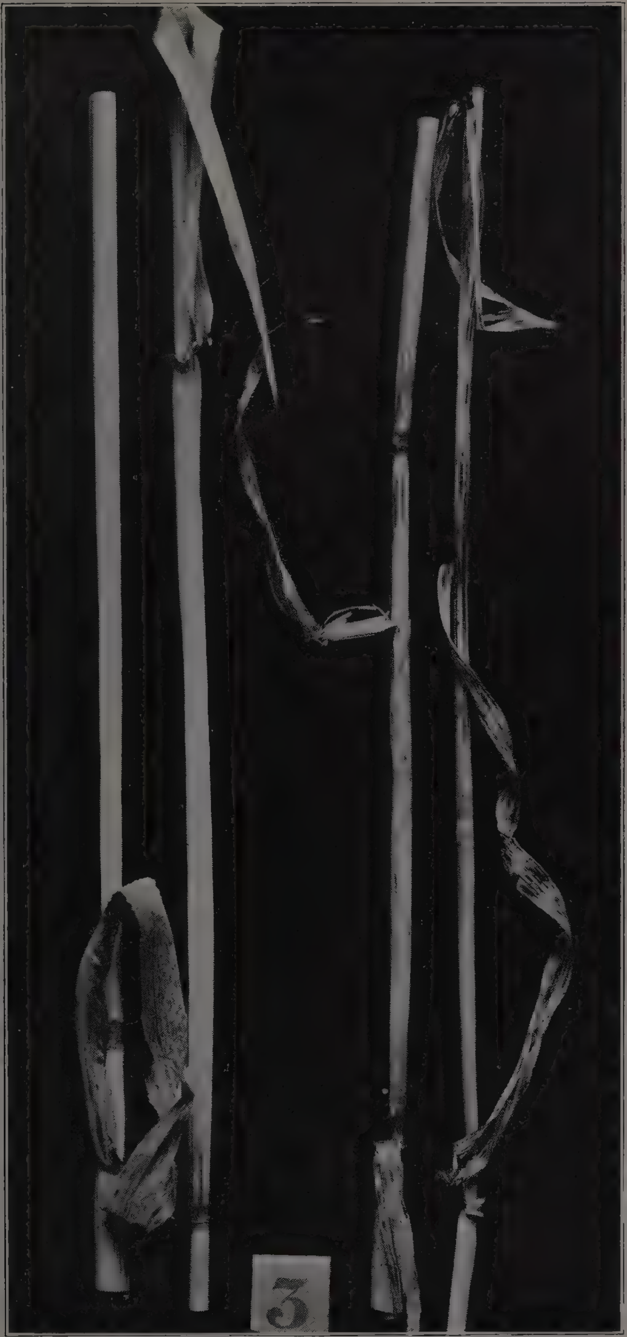

Fig. 9. Reaction of Manchuria and Lion to *H. sativum*.
At left, culms of Manchuria; at right, culms of Lion.

TABLE XVII

Average Reaction of Various Cultures of Manchuria, Lion, and F_3 Lines of the Manchuria-Lion Cross to *H. sativum*

Variety	Year	Average numerical figure									No. of Cult.	Mean	S. D.
		6	9	12	15	18	21	24	27	30			
Manchuria	1921			1	3	5					9	16.3 ± .46	2.06 ± .33
Manchuria	1922							8	5	1	14	25.5 ± .34	1.88 ± .24
Lion	1921	1	2	5	1						9	11.7 ± .55	2.43 ± .39
Lion	1922			2	6	4	1				13	15.9 ± .46	2.46 ± .33
Manchuria × Lion F_3	1921		13	36	60	13	2				124	14.3 ± .20	3.29 ± .14

In 1921 only a single row of each culture was grown, while in 1922 each parent check culture was represented by two rows, while each hybrid culture consisted of 3 rows. Each row of each hybrid line was the progeny from an individually selected plant whose reaction was known. The reactions in 1922 for each line are given in the same order in the table as the reaction for the parent plants. Thus three plants of the line 173, with reaction indices of 6, 11, and 13, were selected in 1921. The progeny of these three plants gave mean reactions of 13.5, 12.7, and 20.7, respectively. There is some evidence in this line of a heterozygous condition. Line 203, however, in which individual plants with reactions of 11, 12, and 20 were selected, produced progeny with average reactions of 24.6, 22.0, and 23.6. The evidence obtained indicates that the line 203 is homozygous and resistant. A careful examination of the results leads one to conclude that some of the hybrid lines are resistant like Manchuria while others

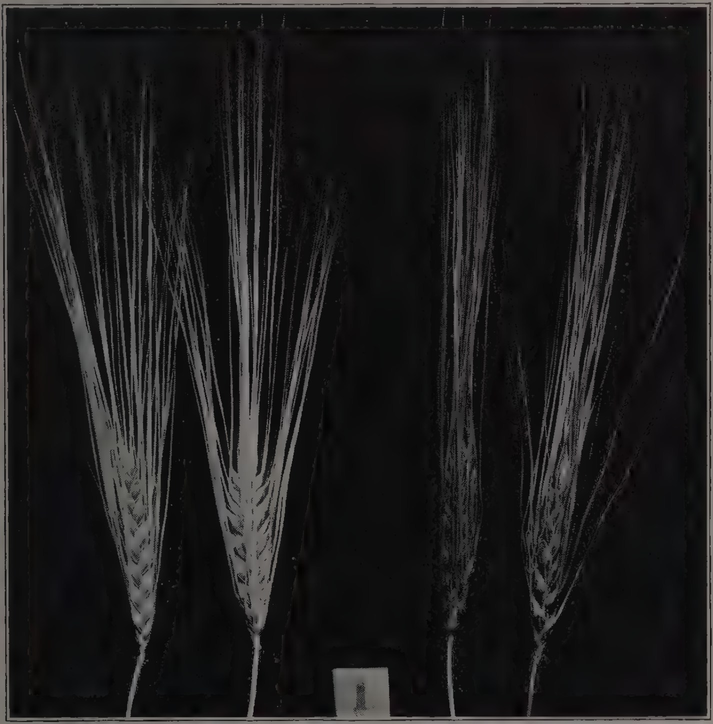

Fig. 10. Reaction of Manchuria and Lion to *H. sativum*
At left, spikes of Manchuria; at right, spikes of Lion.

TABLE XVIII

REACTION TO *H. sativum* OF MANCHURIA, LION, AND F_3 LINES OF THE MANCHURIA-LION CROSS

Variety	Reaction 1921	Mean reaction 1922			Average 1922	Average 1921, 1922	Reaction, parent plants		
Lion	6.9	14.7	15.5	....	15.1	11.0	8	6	..
Manchuria	17.0	26.5	23.8	....	25.2	21.2	14	22	..
166	9.1	24.4	19.6	22.3	22.1	15.6	6	12	14
173	8.4	13.5	12.7	20.7	15.6	12.0	6	11	13
174	7.6	13.8	12.4	....	13.1	10.4	6	10	..
177	9.2	13.9	12.0	11.4	12.4	10.8	6	12	14
181	15.8	18.2	21.5	....	19.9	17.9	12	23	..
185	16.7	22.2	25.0	25.7	24.3	20.5	7	15	23
203	16.6	24.6	22.0	23.6	23.4	20.0	11	12	21
204	15.2	23.7	24.8	23.6	24.0	19.6	11	12	20
Lion	11.1	19.5	....	....	19.5	15.3	13	..	..
Manchuria	15.7	27.8	26.5	....	27.2	21.5	14	18	..
193	10.0	26.4	26.2	....	26.3	18.2	7	15	..
202	7.6	16.9	20.6	19.7	19.1	18.4	7	9	10
229	12.3	18.4	18.7	19.1	18.7	15.5	7	15	16
230	9.5	22.6	22.4	18.2	23.1	16.3	7	14	14
Lion	11.5	19.2	18.4	....	18.8	15.2	7	16	..
Manchuria	18.2	28.9	28.4	....	28.7	23.5	12	22	..
207	15.3	24.2	25.2	....	24.5	19.4	11	12	..
218	16.0	22.4	18.1	23.3	21.3	18.7	11	12	20
219	15.7	22.3	19.2	26.4	22.6	19.2	11	11	21
224	16.1	20.7	25.1	25.6	23.8	20.0	11	13	21
Lion	9.6	13.5	15.5	....	14.5	12.1	7	13	..
Manchuria	13.1	25.4	24.3	....	24.9	18.5	8	16	..
247	14.0	15.0	18.5	18.0	17.2	15.6	11	16	16
248	10.3	16.6	15.3	16.1	16.0	13.2	6	13	13
249	11.4	21.7	24.9	25.0	24.0	17.7	10	15	16
253	10.6	18.8	16.8	19.4	18.3	14.5	7	13	14
Lion	11.2	19.2	18.7	....	19.0	15.1	..	..	..
Manchuria	15.3	26.8	....	....	26.8	21.1	..	..	..
228	15.2	21.5	26.9	28.0	25.5	20.4	12	12	20
235	17.0	19.4	23.9	18.0	20.4	18.7	11	13	22
239	16.4	16.0	15.2	....	15.6	16.0	13	18	..
241	18.7	20.7	17.8	21.7	20.1	19.4	15	15	21
Lion	14.2	16.7	14.7	....	15.7	15.0	11	17	..
Manchuria	17.9	25.2	....	....	25.2	21.6	21	..	..
257	11.9	19.2	17.3	25.6	20.7	16.3	7	17	17
258	12.8	18.8	20.1	16.6	18.5	15.7	6	17	17
259	12.9	13.3	15.0	16.3	14.9	13.9	8	16	19
274	11.8	19.8	22.2	....	21.0	16.4	15	18	
Lion	12.3	9.0	13.8	....	7.6	10.0	4	17	.
Manchuria	14.1	23.8	23.8	....	23.8	19.0	10	18	..
250	15.0	18.7	14.7	18.9	17.4	16.2	13	13	20
260	15.4	19.7	20.2	....	20.0	17.7	9	18	..
262	19.0	18.2	21.9	17.7	19.3	19.2	15	16	22
265	16.9	18.0	18.2	17.0	17.7	17.3	13	14	21
266	22.0	20.0	17.6	17.7	18.4	20.2	19	20	25
267	19.5	17.3	21.8	23.8	21.0	20.3	12	16	24
271	11.8	13.5	16.7	....	15.1	13.5	15	18	..
283	17.5	18.5	19.7	13.5	17.2	17.4	12	14	21
Lion	12.3	13.4	13.1	....	13.3	12.8	10	14	..
Manchuria	14.1	24.8	25.3	....	25.1	19.6	11	18	..

are as susceptible as Lion. Sixteen of the 36 families were selected in F_3 because they appeared as susceptible as the Lion parent. The following, on the basis of combined results for the two years, appear as susceptible as Lion: Lines 174, 177, 229, 230, 248, 253, 259, and 271, and were presumably homozygous in F_3 for susceptibility. The lines which appear resistant on the basis of the two years' study are as follows: Lines 185, 203, 204, and possibly 219, 224, and 228. Line 193, which was apparently susceptible in F_3, appeared highly resistant in F_4, while Line 239, which appeared resistant in F_3, appeared susceptible in F_4.

A correlation coefficient was calculated to determine the degree of correlation obtained from the F_3 result as determined from a single-row trial, and the result as obtained from an average of 3 rows for the various progeny lines in F_4.

TABLE XIX

CORRELATION BETWEEN REACTION TO *Helminthosporium* in F_3 LINES AND F_4 LINES

	Reaction, 1921					
Average reaction, 1922	9	12	15	18	21	
12	2					2
15	2	2	1			5
18	1	3	2	3	1	10
21	1	2	3	2	1	9
24	1	1	4	2		8
27	1		1			2
	8	8	11	7	2	36

$r = .256 \pm .105$

The calculated coefficient of correlation, $+.256 \pm .105$, is about two and a half times its probable error. It seems reasonable to conclude that by the use of several rows of a line systematically distributed over the field, a fairly reliable criterion of resistance and susceptibility could be obtained.

The evidence presented would indicate that from 124 F_3 lines which were grown in F_3, 8 were homozygous for susceptibility and 6 for resistance. Results of this nature could be explained on the hypothesis that Lion and Manchuria differed by two main factors for resistance and susceptibility to *H. sativum*. The presence of both factors might be considered to lead to the production of resistance while the absence of both might be supposed to produce a susceptible type.

Seed from the various plants of a family of 70 of the F_4 lines grown in the field in 1922, was mixed together and planted in the greenhouse in infected soil from the field plot and in sterilized soil inoculated with a culture of *H. sativum*. From the study of various barley varieties, the conclusion was reached that root infection under greenhouse conditions was the best criterion of resistance and susceptibility under field conditions.

A correlation coefficient was calculated to show the degree of correlation in infection under field conditions and the root infection under greenhouse conditions. The correlation coefficient obtained was +.118±.079. From an examination of Table XX it may be noted that several lines which were apparently highly resistant under field test were susceptible under the greenhouse test. The correlation coefficient is so small in relation to its probable error that it is not significant.

TABLE XX

Correlation Between the Reaction to *H. sativum* under Field Conditions of F_4 Lines of the Cross Between Lion and Manchuria with the Average Root Infection of Their F_5 Progeny under Greenhouse Test

Average root infection, greenhouse, 1922-23	Average reaction under field conditions, 1922																
	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
4.5											1						1
5.0							1	1	1		1				1		4
5.5	1					1				1			1	1	1		6
6.0			2	1	2		2								1		8
6.5			1	2	1	1	2	2			1		1		1		12
7.0					1	2	1	2		3	5		1		1		16
7.5				1				1	3		2		1		1		9
8.0						1	1		2				1	1			6
8.5		1						3							1	1	6
9.0														1			1
	1	1	3	4	4	5	7	9	6	4	10	0	5	3	7	1	70

r = +.118±.079

The apparent lack of correlation between field and greenhouse trials might, however, be a result of the inaccuracy of the test rather than a real lack of relation. To further test this point, the thirty-six F_3 families which were selected as possibly homozygous for resistance and susceptibility were used. The average reaction to *H. sativum* in the field in 1921 and 1922 was computed for these 36 families. It will be recalled that only a single row of each was grown in 1921 and that 3 plants were selected in 1921 from each of the 36 families to test in 1922. The average field result for 1921-22 is then based on four rows, one of which was grown in 1921 and the other three in 1922. All three rows of each line were, however, grown side by side in 1922.

The greenhouse work consisted of a test of two of each of the three lines of each of the 36 families except in two cases where only one line was available. The results from these two lines were averaged, each line being tested in sterilized soil which was inoculated with *H. sativum* and in infected soil from the field plot.

A correlation coefficient of +.426±.092 was obtained. This expresses the degree of correlation for the average field reaction in 1921 and 1922 to *H. sativum* of 36 F_3 Manchuria-Lion crosses with the root infection obtained in the greenhouse. This coefficient gives further evidence to prove that resistance and susceptibility to *H. sativum* are inherited characters. The correlation is very much larger than that obtained from the use of a single field row and a single greenhouse test. It gives furher evidence to show that in studying the mode of reaction to *H. sativum* it is essential to use several plots in order to obtain a reliable result. Replication would certainly be of value in a study of this nature.

TABLE XXI

CORRELATION BETWEEN AVERAGE REACTION TO *H. sativum* IN THE FIELD UNDER F_3 AND F_4 TEST OF 36 F_3 LINES OF THE CROSS LION × MANCHURIA WHICH WERE SELECTED IN F_3 EITHER AS RESISTANT AS MANCHURIA OR AS SUSCEPTIBLE AS LION WITH THE AVERAGE REACTION AS DETERMINED BY THE ROOT INFECTION UNDER GREENHOUSE CONDITIONS

Average reaction on roots in greenhouse	Average reaction in field, 1921-22												
	10	11	12	13	14	15	16	17	18	19	20	21	
5.0	1				1		1						3
5.5									1	1			2
6.0		1		1		1	1		1	2			7
6.5					1		3	1	1	1		1	8
7.0							3	1			3		7
7.5			1				1		2	1	1		6
8.0										1	1		2
8.5											1		2
	1	1	1	1	2	1	9	2	5	6	6	1	36

r = +.426±.092

CORRELATION BETWEEN REACTION TO H. SATIVUM AND BOTANICAL CHARACTERS

Because of the difficulty of determining the exact genetic nature of a particular F_3 family in relation to resistance and susceptibility, it seems unwise to make an extended analysis of the possible correlation between the genetic nature as to resistance and susceptibility and the genetic condition for botanical characters. Perhaps some idea of the possibilities may be reached by a consideration of the families which appeared to be either resistant or susceptible as determined by the F_3 and F_4 studies. The facts are presented in Table XXI.

Of the susceptible families, 2 were homozygous for black color; one was homozygous for white; 5 were heterozygous for black vs. white; 4 were smooth-awned, 3 of which were heterozygous for degree of smoothness of the awn; and one was smooth-awned. Of the black homozygous families both segregated for degree of smoothness of awn.

TABLE XXI

BOTANICAL CHARACTERS OF THE FAMILIES OF THE LION-MANCHURIA CROSS WHICH APPEARED TO BE EITHER HOMOZYGOUS FOR RESISTANCE OR SUSCEPTIBILITY TO *H. sativum* AS DETERMINED BY F_3 AND F_4 TESTS

Line No.	Homozygous for	Botanical description
174	Susceptibility	Black, segregating for degree of smoothness of awn.
177	Susceptibility	Black, segregating for degree of smoothness of awn.
229	Susceptibility	Heterozygous for black vs. white, heterozygous for rough vs. smooth awn.
230	Susceptibility	Heterozygous for black vs. white, homozygous for rough awn.
248	Susceptibility	Heterozygous for black vs. white, homozygous for smooth awn.
253	Susceptibility	Homozygous for white, heterozygous for degree of smoothness of awn.
259	Susceptibility	Heterozygous for black vs. white, heterozygous for rough vs. smooth awn.
271	Susceptibility	Heterozygous for black vs white, heterozygous for degree of smoothness of awn.
193	Resistance	Heterozygous for black vs. white, heterozygous for rough vs. smooth awn. Both rough- and smooth-awned families were obtained in F_4.
203	Resistance	Homozygous for white color and rough awn.
204	Resistance	Homozygous for white color and rough awn.
219	Resistance	Homozygous for white color, heterozygous for rough vs. smooth awn. Homozygous intermediate smooth and homozygous smooth-awned families were obtained in F_4.
224	Resistance	Homozygous for white color, heterozygous for rough vs. smooth awn. A smooth-awned family which segregated for degree of smoothness of awn was obtained in F_4.
228	Resistance	Heterozygous for black vs. white, heterozygous for degree of smoothness of awn. An intermediate smooth-awned family was obtained in F_4.

Of the resistant families, 2 were homozygous for both white color and rough awn like the resistant Manchuria parent. Two others were homozygous for white color and segregated for rough vs. smooth awn.

From these families smooth-awned lines were obtained in F_4. Two other families were heterozygous for black vs. white, one of which segregated for rough vs. smooth awn, and the other produced all smooth-awned plants, altho there was considerable variation in the smoothness of the awn.

These facts show, as far as they go, that there is a tendency for a greater proportion of the resistant families to be of white color and rough awn than in the susceptible group. They likewise prove that if there is a linkage between resistance and susceptibility and botanical characters the linkage is not very close, for out of 124 F_3 lines all possible combinations of resistance and susceptibility with various types of characters were obtained.

The greenhouse reactions of the families 174 ,177, 229, 230, 248, 253, 259, and 271, which were apparently homozygous for susceptibility, were as follows: 5.25, 6.00, 7.50, 6.25, 6.25, 6.00, 6.75, and 5.00. All were susceptible in the greenhouse test except family 229. The greenhouse reactions of the families 193, 203 ,204 ,219, 224, and 228, were 5.5, 7.25, 8.5, 8.0, 7.0, and 7.75. All appear resistant except family 193. The greenhouse reactions of Lion were 7, 6, 6, 6, 7, 7, and of Manchuria 8, 8, 7.5, 8, 6.5, 7.5, 8. The susceptible hybrids were apparently more susceptible under greenhouse conditions than Lion. It has been noted previously that Lion is less severely infected under greenhouse conditions than many varieties belonging to the susceptible group.

As the data on the hybrid lines were taken without a knowledge of the previous year's results, it seems apparent that a test of infection under greenhouse conditions might be of some value as a means of isolating resistant families and of discarding susceptible ones.

SUMMARY

1. Crosses between Lion, a six-rowed, black, smooth-awned variety, which is susceptible to attacks of *H. sativum;* and Manchuria, a six-rowed, white, rough-awned, resistant variety, have been used to determine the mode of inheritance of the differential characters, rough vs. smooth awn, black vs. white color, and susceptibility vs. resistance.

2. The rough-awned character proved dominant to smooth awns and in F_2 the ratio of rough- to smooth-awned plants approximated 3:1. There were different degrees of smoothness of awn, some plants producing small teeth on approximately the upper third of the awn only, while other smooth-awned plants produced teeth on approximately the upper two thirds of the awn. While in this cross the rough vs. smooth-awn character appeared to be dependent on a single

factor difference, the degree of smoothness of the awn appeared to be dependent upon modifying factors which were apparently brought in by the rough-awned parent.

3. Some lines bred true in F_3 and in later generations for various degrees of smoothness of the awn, which would appear to justify the use of the hypothesis of modifying factors instead of the possible hypothesis of gene variability.

4. Black vs. white color was apparently dependent upon a single genetic factor which was inherited independently from the main factor difference for rough vs. smooth awn.

5. One hundred and twenty-four F_3 lines of the Manchuria-Lion cross were grown in rows of 25 plants each and sprayed with spore suspensions of *H. sativum.* Cultures of Lion and Manchuria were grown every tenth to twentieth row as checks. On the basis of the individual plant data for susceptibility or resistance, all F_3 lines were selected which appeared as resistant as Manchuria or as susceptible as Lion and were again tested in F_4. By this test 8 lines were obtained which were as susceptible in both F_3 and F_4 as Lion and 6 lines which were approximately as resistant as Manchuria.

6. The correlation coefficient for the degree of infection in F_3 and F_4 of 36 hybrid lines of Lion×Manchuria was .256±.105.

7. The 36 hybrid families were tested for root infection under greenhouse conditions in 1922-23. The correlation coefficient for average severity of infection under field conditions for F_3 and F_4 as related to root infection under greenhouse conditions was .426±.092.

8. Resistance and susceptibility to attacks of *H. sativum* are inherited characters altho apparently dependent on more than a single genetic factor.

9. A greater proportion of the resistant families was of white color and rough awn than of the susceptible families; however, within the 124 F_3 lines grown, all combinations of resistance and susceptibility, smooth and rough awn, and black vs. white color were obtained.

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Agricultural Experiment Station

Root-Rots of Wheat

A. W. Henry
Division of Plant Pathology and Botany

UNIVERSITY FARM, ST. PAUL

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ROOT-ROTS OF WHEAT

By A. W. Henry[1]

INTRODUCTION

Root-rots of wheat and other cereal plants have been known for several years. Bolley was perhaps the first to emphasize the importance of these diseases in this country. He considered that root-rots were caused by several imperfect fungi which tend to accumulate in the soil as a result of more or less constant cropping to one kind of grain. In his estimation, root-rots were chiefly responsible for the unproductiveness of many of the wheat lands of the Northwest, rather than depleted soil fertility or toxic substances in the soil. Other workers at the Minnesota Agricultural Experiment Station and elsewhere have since corroborated many of Bolley's ideas.

As most of the publications on root-rots of wheat deal with them only incidentally, it seemed desirable to investigate them in particular, combining in this study both a comprehensive survey of possible root-rotting fungi and controlled inoculation studies to determine their relative pathogenicity. The plan followed has been to isolate fungi from as many sources as possible but particularly from such as are intimately associated with wheat rots in nature. Extensive inoculations were made and the most destructive and less familiar pathogenes were studied in greatest detail. While it is possible that micro-organisms other than true fungi may cause root-rots of wheat, only the latter were studied by the writer.

The roots of the wheat plant are very important in the economy of the plant, as they determine in large measure what the development of the above-ground parts shall be. Livingston (45), for instance, found that stunted wheat tops were associated with poor root development. Root-rots inhibit root growth, destroy absorbing cells, and by attacking the vascular system prevent the transportation of water and food materials. They consequently cause poorly developed tops.

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[1] The writer gratefully acknowledges the helpful advice and criticism of Dr. E. C. Stakman, under whose direction the work was done. He also desires to express his appreciation to Dr. Louise Dosdall, Dr. J. G. Leach, and others to whom he is indebted for assistance of various kinds.

HISTORICAL

There is a comprehensive literature on foot- and root-rots of small grains, but there is comparatively little definite information on root-rots of wheat. The occurrence of fungi in association with rotted cereal roots is mentioned by several workers, but only rarely are inoculation experiments reported, or is any proof of the parasitism of the fungi given. There are, however, a few exceptions.

Root-rots of wheat are frequently attributed to species of *Fusarium.* For instance, Bolley (7) claims that *Fusarium spp.* are important root-rotting organisms of wheat and other cereals. Various European workers, Ihssen (34), Mortensen (52), and Schaffnit (68), for example, state that *Fusarium nivale* Ces. causes root-rot, foot-rot, and seedling blight of cereals. Stakman (75) found *F. culmorum* (W.G.Sm.) Sacc. very destructive to the roots of durum wheat seedlings in agar cultures. Atanasoff (1) considers that *Gibberella saubinetii* (Mont.) Sacc. (*Fusarium graminearum* Schwabe) is one of the chief causes of root-rot of cereals in the United States. However, he states that according to his observations, *Fusarium herbarum* (Corda) Fries, *F. avenaceum* (Fr.) Sacc., *F. culmorum* (W.G. Sm.) Sacc., and *F. culmorum* (W.G. Sm.) Sacc. *var. leteius* Sherb., are as important as *Gibberella saubinetii. Fusarium arcuosporum* Sherb., *F. scirpi* Lamb. and Fautr., *F. solani* (Mart. pr.p.) Ap. and Wr., *F. arthrosporioides* Sherb., and *F. redolens* Wr. and also mentioned as being not unimportant in the root-rot problem. In a more recent paper (2), however, he mentions only *G. saubinetii, F. avenaceum,* and *F. herbarum* as causing root-rots of wheat but says that *F. culmorum* attacks the young seedlings in the same way as does *G. saubinetii.* He reports the occurrence, altho rarely, of *Calonectria graminicola* (Berk. and Brm.) Wr. (*F. nivale*) in the United States. An extensive bibliography of the literature on the *Fusaria* of cereals is given.

For several years Bolley (7, 8) has reported that species of *Helminthosporium* are destructive pathogenes of wheat roots in North Dakota. Johnson (38) used *Helminthosporium gramineum* Rabh. (more probably *H. sativum* P.K. and B.) in inoculation experiments. The roots of wheat plants from inoculated seed were discolored near the root crown and were also much shorter and less vigorous than those of check plants. Drechsler (20) cites papers by Bassi and Palm which report the occurrence of *Helminthosporium gramineum* Rabh. on wheat in Italy and Java, respectively. According to Bassi a decortication of wheat roots is caused by this fungus. Drechsler, however, points out the similarity of the symptoms produced to those caused by *H. sativum* and infers that the latter fungus was probably mistaken for *H. grami-*

neum by both workers. Stakman (75), in 1920, reported that the roots of wheat plants in Minnesota were frequently infected with a species of *Helminthosporium* similar to or identical with *H. sativum* P.K. and B. Such roots were partially or entirely brown and often developed loose cortices. Similar symptoms were produced by artificial inoculations. The writer isolated a *Helminthosporium* (tentatively determined as *H. sativum*) from wheat, rye, and barley, in Western Canada.[2] Artificially inoculated seeds of wheat, rye, and barley developed badly diseased seedlings in test-tube cultures, both roots and tops being affected. Oats were only slightly injured. In pot cultures similar results were obtained, but the disease in these tests was most noticeable as a foot-rot and a leaf-spot of the seedling leaves. *Helminthosporium* root-rots were reported from New York by Kirby (83) and from Idaho by Hungerford (83), in 1921, and by Raeder (62) in 1922. Hamblin (28) described abnormal roots as one of the symptoms of a disease of wheat caused by *Helminthosporium* in Australia. He considered this disease more serious than the true take-all. Christensen (13) was able to infect 98 species of grasses with *H. sativum.* Wheat, barley, and rye were the most susceptible cereals, while oats was either immune or highly resistant. All parts of a susceptible host, including the roots, were attacked. Both primary and secondary roots were severely rotted. Kanred wheat[3] C.I. 5146, was quite resistant to root infection.

Dosdall (19) studied the factors influencing the pathogenicity of *H. sativum,* giving particular attention to root- and foot-rots. She found that wheat and barley roots developed rather limited local lesions which killed the root tips or cut off portions or even whole roots when the lesions occurred back of the tips. In general, she found that the disease caused greatest injury when conditions for host development were unfavorable. Stevens (78, 79, 81) studied the relation of a species of *Helminthosporium* (of the *H. sativum* group) to a foot-rot of wheat in Illinois. He (79, 81) showed by artificial inoculations that it was a root parasite also, but investigated this phase of the disease only incidentally. Weniger (86) found a fungus similar to *H. sativum* causing lesions in the cortex of both the roots and the shoots of young seedlings, from black-pointed wheat seeds.

Numerous investigators have reported a discoloration and rotting of the roots as one of the symptoms of the true take-all disease of wheat. Stevens (77), in an extensive historical and bibliographic sketch on foot-rot of wheat, cites numerous papers in which mention is made of the blackening and death of wheat roots attacked by *Ophiobolus;* for instance, those of Frank (1894-95), Mangin (1898-99,

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[2] Unpublished thesis, University of Saskatchewan, May, 1920.

[3] C.I.=Cereal investigations accession number of the Bureau of Plant Industry, U. S. Dept. of Agr.

1914), McAlpine (1902), Richardson (1910), Eriksson (1912), and Spafford (1917). *Leptosphaeria* also is said to cause a similar brown or black discoloration of the roots (Mangin, 1914). More recently Kirby (41) described the symptoms of the disease as they occur in this country. He pointed out that *Ophiobolus cariceti* (B. and Br.) Sacc., is confined to the roots and lower internodes of the host, where a pronounced discoloration occurs. Rosen and Elliot (63) believe that *O. cariceti* attacks only weakened plants.

In 1919 Selby and Manns (73) reported a new anthracnose disease of cereals in Ohio, caused by *Collectotrichum cereale* Manns. This fungus was said to be parasitic on the roots, culms, blades, and spikes of rye, and on the roots, culms, and blades of wheat, oats, barley, and several grasses. The pathogene, however, attacked wheat roots less severely than those of rye. Bolley (7, 8) has frequently reported *Colletotrichum* as one of the genera responsible for soil sickness and root-rots of cereals in North Dakota. Stakman (76) showed that *Colletotrichum phomoides* (Sacc.) Ches., isolated from a diseased tomato, was somewhat parasitic on the roots of wheat and oats, but she did not consider that it would be destructive in the field.

Bolley (7, 8) stated that *Alternaria* often caused decortication of wheat roots. *Macrosporium* was reported several times on wheat roots but later work indicated that this was mostly *Alternaria*. Johnson (38) inoculated wheat seeds with *Alternaria* but no root infection resulted. Stakman (76), however, isolated parasitic strains of *Alternaria* from cereal seeds and from the soil. These strains readily infected wheat roots both in agar cultures and in sterile sand. Stevens (81) inoculated wheat seedlings in rag-doll germinators with an *Alternaria* obtained from wheat seeds. He observed that the hyphae penetrated the cells of the root cortex and caused a slight browning.

Rhizoctonia has been found several times on cereal roots. Peltier (59) found it on corn roots in the field in Illinois, and lists its occurrence on corn in two other states and on side oats from Idaho (reported by Temple). He also cites a paper by Reuter, who studied a root-rot of rye caused by *Rhizoctonia* in Finland. Bessey (82) reported a *Rhizoctonia* root-rot of wheat in Michigan, occurring especially in heavy soils. Piper and Coe (61) list a large number of susceptible lawn grasses. Stevens (81) found *Rhizoctonia* on the roots and stems of wheat in Illinois. Stakman (76) isolated *Rhizoctonia* from the underground parts of rye, wheat, and oat plants in the field in Minnesota. A few artificially inoculated durum wheat roots became infected, but the tissues were apparently not disorganized.

In addition to the fungi previously mentioned, Stakman (76) showed that the following are parasitic on the roots of durum wheat: *Botrytis sp.*

from rye, *Gliocladium sp.*, and *Tilachlidium sp.* *Sclerotium rolfsii* Sacc. also was capable of attacking the base of the culms of durum wheat seedlings and of spreading into the roots after the tissues had become weakened. The latter fungus has also been reported by Godfrey (26) as the cause of small brown lesions on wheat crowns. The following fungi were also used by Stakman in inoculation experiments on durum wheat seedlings, but they were not parasitic on the roots: *Acrostalagmus albus* Preu., *Aspergillus niger* Van Tiegh., *Botrytis cinerea* Pers., *Botrytis fascicularis* (Cda.) Sacc., *Cephalothecium roseum* Cda., *Cladosporium cucumerinum* E. and A., *Cladosporium fulvum* Cke., *Monascus purpureus* Went., *Penicillium chrysogenum* Thom., *Rhizopus nigricans* Ehr., *Sclerotinia libertiana* Fel., *Sphaeronema fimbriatum* (E. and H.) Sacc., *Vermicularia circinans* Berk., *Verticillium candelabrum* Bonord., and *Sporotrichum poae* Pk.

Chen (12) found a sterile fungus with a septate mycelium which attacked the roots of wheat seedlings in test-tube cultures.

It is interesting to note that species belonging to at least twelve genera of fungi have been reported in the literature as parasitic on wheat roots.

ROOT SYSTEM OF THE HOST

The development and morphology of the wheat root system is described in detail by Percival (60). The following is based largely on his description. Two distinct set of roots are produced, the seminal and the adventitious. The former arise from the hypocotyl and begin to develop when the grain germinates. Eight seminal roots in all may be formed. They are slender, uniform in diameter, develop a number of fine lateral branches, and bear a very abundant covering of root hairs for some distance back of the root tips. These die off and new ones are formed near the growing point as the roots elongate. The seminal roots are apparently of most importance during the seedling stage of the plant, supplying it with water, but seem to remain functional throughout its life.

A considerable interval, often several weeks, may intervene between germination and the development of the adventitious or permanent roots. These are essentially fibrous. They arise in pairs from the basal nodes of the primary axis, usually just below the surface of the soil regardless of the depth at which the seed is planted. Succeeding shoots develop their own systems of permanent roots in a somewhat similar manner. The permanent roots are larger in diameter, longer, branch more profusely, and are more numerous than the seminal roots. They are usually most abundant in the upper foot of the soil but some extend four or five feet into the soil and to even greater depths.

METHODS AND MATERIALS USED IN THE ISOLATION OF FUNGI

The isolation of fungi was begun in January, 1921, and continued for approximately a year and a half. Cultures were secured from the seed, roots, and culm bases of wheat, from the corresponding parts of other cereals commonly grown in rotation with wheat, from the soil, and a few from other sources.

Between 500 and 1000 cultures were isolated. This number, however, was reduced to about three hundred by discarding duplications and retaining only those which were different or which came from different sources.

ISOLATIONS FROM SEED, ROOTS, AND OTHER PLANT PARTS

Wheat seed was obtained from eighteen states of the United States, from three provinces of Canada (Manitoba, Saskatchewan, and Alberta), from Mexico, and from the Argentine. Most of it was commercial grain grown in 1920, and much of it was obtained through the courtesy of the Washburn-Crosby Milling Company, of Minneapolis. Professors G. H. Cutler and W. P. Fraser each kindly sent samples from Alberta and Saskatchewan, respectively.

The seeds were surface sterilized at first by immersing them for ten minutes in a 1 to 1000 corrosive sublimate solution, followed by a thoro washing in sterile distilled water. This was a very time-consuming operation when a large number of samples had to be handled. A quicker method was therefore adopted which consisted of dipping the seeds in 70% ethyl alcohol, then immersing them in corrosive sublimate solution, 1 to 1000, for from 3 to 5 minutes, then dipping them again in 70% alcohol and plating the seeds directly on potato dextrose agar in petri dishes. This method was also used for other plant parts, and is the same as that used by Christensen (13) except for the strength of alcohol. Roots and underground parts were then frequently plated on acidified agar to prevent the growth of bacteria. The fungi were allowed to develop at room temperature for a few days and then transfers were made from the borders of colonies to slants of potato dextrose agar in test tubes.

ISOLATIONS FROM THE SOIL

Numerous isolations of fungi were made from "sick soils," particularly from the three following: (1) A soil from the plant pathology field plots, University Farm, St. Paul. This soil had been used for several years as a disease garden in the study of imperfect fungi on cereals. (2) Soil from a continuous-wheat plot from the rotation plots of the agronomy department, University Farm. Wheat had been grown on this plot every year since 1893, except 1915 and 1916, when it was in corn in order to control wild oats. (3) A continuous-wheat plot soil from the Dominion Experimental Farm at Brandon, Manitoba.[4] This plot was first sown to wheat in 1911 and had grown eleven successive crops of wheat when the samples were taken. The first samples from these plots were taken during the last week of September and the first week of October, 1921. Additional samples were obtained from the St. Paul plots at intervals during the following summer.

In order to be reasonably sure that the fungi isolated were largely from the soil and not surface contaminations from the air, precautions similar to those used by Jensen (35) were observed in taking samples in the field.

In the collection of samples at St. Paul, small quantities of soil were taken from several locations on each plot, and these were later mixed together before isolations were made. This was done in order to secure a more representative sample of the soil of each plot.

Fungi were isolated directly from the soil by two methods: (a) A dilution method in which approximately one gram of soil was transferred to a flask containing 100 cc. of sterile distilled water. This was thoroly shaken and a platinum loopful of this extract, or of further dilutions, transferred to each of several test-tubes of acidified melted agar and immediately poured into petri dishes; (b) by directly transferring small lumps of soil by means of a sterilized platinum loop to the surface of agar in petri dishes. Several media were used, including unacidified potato dextrose agar, acidified potato dextrose agar, soil agar, Jensen's III (35), and an acid-raisin agar recommended by Waksman (85). Acid agars were used in order to keep down bacteria. The fungous colonies, however, frequently outgrew the bacteria on unacidified agar. The plates were incubated at room temperature and at four other temperatures ranging from 7 to 33° C., in order to permit the growth of fungi with different temperature optima.

Soil fungi were isolated indirectly by sowing sterile seedlings on sick soil.[5] This soil was brought from the field in new bags and placed in sterilized pots in the laboratory. The sterile seedlings were then planted and after about three weeks' growth their roots were washed free of soil and examined for disease. Portions of roots showing lesions were then surface sterilized and plated on agar, and fungi were isolated from them. Even with these precautions, it is possible that all the fungi developing on the roots were not from the soil. However, the purpose was to secure fungi pathogenic on the roots rather than to investigate the fungous flora of the soil.

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[4] Furnished through the courtesy of W. C. McKillican and S. J. Sigfusson, superintendent and assistant superintendent, respectively, of the Dominion Experimental Farm, at Brandon.

[5] Method of obtaining sterile seedlings is given on page 10.

PURIFICATION OF THE CULTURES

Before inoculation experiments were attempted most of the cultures were purified by subculturing. Obviously this was not possible with several which failed to sporulate. Certain cultures were originally started from single spores. Monosporous cultures were also made from others which proved pathogenic and which were desired for more careful study.

METHOD OF SECURING DISEASE-FREE SEEDLINGS

Disease-free seedlings were necessary for the isolation of fungi indirectly from the soil, as previously stated. They were also required for inoculation studies, and a better method of seed sterilization than that used in the isolation of fungi was needed for pathogenicity tests in the greenhouse. Following the suggestion of Selby and Manns (73), Braun (11), and Norton and Chen (56), it was found that presoaking the seed increased the germicidal efficiency of the disinfectant (Table I). It was also found that in order to obtain uninjured seedlings it was advisable to wash the seeds finally in sterile water, rather than to plate them directly from alcohol. The following method of seed sterilization was therefore used for a time: Presoak in water from six to twelve hours; dip in 70 per cent ethyl alcohol; immerse for from two to five minutes in a 1 to 1000 corrosive sublimate solution, wash in sterile distilled water. The effects of this treatment are not shown in Table I, but they were similar to those shown by No. 4 in this table, except that the seeds were not injured by a final dip in alcohol. It was later found that a silver nitrate treatment essentially similar to that used by Dosdall (19) and based on Schröder's (72) treatment, was more effective, and this method was used subsequently. (See No. 6, Table I.) After sterilization, the treated seeds were plated on potato dextrose agar in petri dishes and allowed to germinate at room temperature, or were thoroly dried for future sowing in the greenhouse. When the plumules of the seedlings were approximately 1 cm. long, those showing no evidence of fungous growth around them were selected as sterile seedlings. While occasionally some of these seedlings did later show evidence of contamination when grown under sterile conditions, this was the exception, especially when bright, plump seeds were selected.

TABLE I

Effect of Preliminary Seed Treatment Tests on Marquis Wheat

No.	Treatment	No. of seeds treated	Per cent germination	Per cent yielding fungi	Effect on seedlings
1.	Dipped in 70% alcohol; immersed from 2 to 5 minutes in corrosive sublimate solution 1-1000; dipped in 70% alcohol	32	97	81	Injured
2.	Dipped in 70% alcohol; immersed from 2 to 5 minutes in corrosive sublimate solution 1-1000; washed in sterile water	100	100	77	Not injured
3.	Presoaked 12 hours; immersed 5 minutes in alcoholic corrosive sublimate solution (2 gms. per 1000 cc. 70% alcohol); washed once in 70% alcohol; washed thrice in sterile water	125	0	41	Seed killed
4.	Presoaked 12 hours; dipped in 70% alcohol; immersed from 2 to 5 minutes in corrosive sublimate solution 1-1000; dipped in 70% alcohol	80	86	46	Injured
5.	Immersed 12 hours in N/100 silver nitrate solution; washed in sterile sodium chloride solution; dipped in 70% alcohol	46	85	0	Injured
6.	Immersed 7 hours in N/100 silver nitrate solution; washed in sterile sodium chloride solution; washed in sterile water	188	98	23	Not injured

EXPERIMENTAL RESULTS

FUNGI CARRIED BY THE SEED

FUNGI CARRIED BY WHEAT SEEDS IN GENERAL

It would be expected that there would be many fungous spores on the surface of wheat seeds. Bolley (7) found spores of fifteen different genera of fungi in the washings of wheat seed coats in North Dakota, while the following were obtained from seeds treated for one minute with a dilute formalin solution: *Alternaria, Colletotrichum, Macrosporium, Fusarium, Cephalothecium, Helminthosporium,* and *Penicillium.* He concluded from these results that practically all of the fungi which he and his collaborators had shown to be destructive to the roots of wheat, reached the seed before it was mature.

Hoffer (32) tested the surface sterilized seed of 34 varieties of wheat in Indiana and found 14 free from fungi of any kind, 13 infected with *Fusarium*, 4 with an internal *Macrosporium*, while a *Fusarium* and a *Macrosporium* were isolated from 3. An alcoholic solution of corrosive sublimate was used as a disinfectant.

Wollenweber (89) obtained the following genera from seeds cultured in Germany: *Verticillium, Spicaria, Alternaria, Trichothecium, Langloisula, Ramularia, Melanospora, Leptosphaeria, Helminthosporium, Gibberella,* and *Fusarium* (three species). The mycelium of some was superficial while that of others was internal.

Sherbakoff (71) cultured several samples of wheat seed and concluded that the most common *Fusarium* of wheat in Tennessee, as in other states, was *F. graminearum* Schwabe (*Gibberella saubinetii*) while *Fusarium moniliforme* Sheldon was not common on wheat seed.

Christensen (13) found *Helminthosporium sativum* P. K. and B. prevalent on wheat seeds obtained from widely separated localities.

Stakman (76) found *Alternaria, Tilachlidium*, and *Fusarium* on or in wheat seeds, the former being particularly persistent. She (74) also frequently isolated *Helminthosporium*.

The writer found great variation in the fungi on different seed lots. Poor seed, especially samples showing evidence of weathering, immaturity, sprouting, or other defects, was particularly heavily infected; whereas bright, plump, well-matured samples seemed comparatively free from infection. All seeds tested were superficially sterilized as previously described. In general, *Alternaria* was most commonly isolated from wheat grains and apparently is almost universally distributed. *Fusarium graminearum* Schwabe (*Gibberella saubinetii* (Mont.) Sacc.), however, was obtained almost invariably from scabby kernels. Other species of *Fusarium* were frequently isolated, but less commonly than the one named. *Fusarium moniliforme* Sheldon was isolated from seed from widely separated localities, but it was not found commonly. *Helminthosporium sativum* P. K. and B. was usually the most prevalent fungus in black-pointed kernels. It was also frequently isolated from kernels showing no discolorations and is undoubtedly the most common species of *Helminthosporium* on wheat seeds. Another *Helminthosporium*, with narrower spores than those of *H. sativum*, which we shall designate as *Helminthosporium N*, was found several times in cultures of black-pointed seeds. Several small-spored *Helminthosporia*, which we shall consider collectively as *Helminthosporium M*, were obtained in similar cultures. These forms are apparently wide-spread but not particularly prevalent. *Stemphylium, Cladosporium, Torula, Chaetomium, Penicillium, Aspergillus, Epicoccum, Cephalosporium,* *Acrostalagmus, Cephalothecium*, and *Trichoderma*, as well as several unidentified non-sporulating forms possibly belonging to the *Mycelia Sterilia*, were also isolated from the seed.

FUNGI FOUND IN BLACK-POINTED WHEAT SEEDS

One of the most characteristic discolorations of the seed is "black-point," so named by Bolley because of the conspicuous dark brown or creosote-colored embryos of affected grains. On account of the prevalence of such kernels in apparently good samples of seed wheat, it was considered that these might be important as carriers of root-rotting fungi. Hence an attempt was made to determine the causal organisms and their ability to cause root-rot.

Various investigators have reported the widespread occurrence of black-point and have endeavored to determine its cause. Bolley (7), in 1911 and in 1913 (8), reported the isolation of *Alternaria, Helminthosporium*, and *Fusarium* from black-pointed wheat kernels. He pointed out that *Alternaria* was most commonly associated with black-pointed grains, but stated further that these symptoms might be caused by several fungi. No inoculation experiments were reported, however.

Güssow (27), in 1911, received samples of wheat containing kernels affected with black-point from widely separated regions of Canada (Ontario and Saskatchewan). Germination of these grains did not appear to be impaired, but the seedlings from them were less vigorous than those from normal seeds.

Coons (16) considered that black-point was a disease, or a series of diseases, of little economic importance, which had been present in Michigan for many years. Affected grains germinated well and no distinct lesions formed on the seedlings. He found the diseased tissue swarming with bacteria, which, according to Dr. E. F. Smith, resembled *Bacterium viridi-lividosum*.

Lucia McCulloch (54), in 1920, described a blackening of the embryo ends of wheat kernels from spikelets affected with basal glume rot of wheat. She proved that the disease was caused by a new species of bacterium, *Bacterium atrofaciens* McCulloch.

Stakman (75) reported dark brown blotches on wheat seeds attacked by *Helminthosporium*, but did not mention any particular localization of the discoloration at the germ ends.

The writer (31) inoculated immature wheat heads in various stages of development in the greenhouse at Saskatoon, Sask., with three strains of *Helminthosporium* (tentatively determined as *H. sativum*) from wheat, barley, and rye. Typical black-point developed on numerous kernels in the inoculated heads. Some kernels, especially those from heads inoculated in the early stages of development, showed brown lesions extending over other parts of the seed as well as the embryo, but usually the discolorations were most pronounced at the germ end. The typical fungus was later recovered from the diseased kernels.

Nevada S. Evans (24) isolated a *Helminthosporium* similar to *H. sativum,* in most instances from black-pointed durum wheat kernels. Artificial inoculations were made in the field on the durum wheat varieties Acme and Pentad, in the flowering stage. Many black-pointed kernels developed in the inoculated heads in contrast to a low percentage in the controls.

Christensen (13) noted that the germ ends of wheat seeds were most conspicuously discolored by *H. sativum.*

Weniger (86) stated that black-pointed kernels of durum wheat in North Dakota, tho sometimes shriveled, were usually normal in weight but frequently germinated poorly and produced blighted seedlings.

Drechsler (20) reported low viability of wheat seeds discolored by *H. sativum.* He also noted that a lighter brownish discoloration of the seeds was associated with *Alternaria* and other fungi.

The writer found black-pointed kernels frequently in samples of common wheat from different parts of the United States and Canada and in two samples from the Argentine. A sample of Red Bobs wheat from Western Canada contained 34 per cent of these kernels. A lot of Marquis wheat grown at St. Paul in 1920, and containing 13.4 per cent black-pointed kernels, was used in the following cultural studies.

Two hundred normal seeds and two hundred black-pointed seeds were selected from this sample, presoaked for seven hours, surface sterilized in corrosive sublimate solution, 1 to 1000, washed in sterile distilled water, and plated on potato dextrose agar in petri dishes. The cultures were incubated at room temperature until the colonies of fungi growing out from the seeds were sporulating abundantly. They were then examined, and counts were made of the different fungi which had developed. The results of this test are recorded in Table II.

When the seeds germinated, some were raised off the agar by the growth of the young seedlings before any fungi grew out from them. The percentage of total seeds yielding fungi is therefore, no doubt, lower that it would have been had this not occurred. It is quite evident that *H. sativum* was the most common fungus associated with black-point in this sample and that it was much more common on diseased kernels than on normal kernels. It is also significant that two other apparently distinct species of *Helminthosporium* were obtained from the black-pointed kernels and not from normal ones.

TABLE II

COMPARISON OF THE FUNGOUS CONTENT OF BLACK-POINTED AND NORMAL MARQUIS WHEAT SEEDS FROM THE SAME SAMPLE

Fungi developing	Black-pointed seeds			Normal seeds		
	No. seeds plated on agar	Per cent of total seeds plated	Per cent of seeds yielding fungi	No. seeds plated on agar	Per cent of total seeds plated	Per cent of seeds yielding fungi
Helminthosporium sativum	97	48.5	73.5	4	2.0	33.3
Helminthosporium N	5	2.5	3.8	0	0.0	0.0
Helminthosporium M	5	2.5	3.8	0	0.0	0.0
Alternaria	14	7.0	10.6	5	2.5	41.7
Other fungi	11	5.5	8.3	3	1.5	25.0
None	68	34.0	...	188	94.0	...

A comparison also was made of the relative value for seed purposes of black-pointed kernels and normal kernels from the same sample of Marquis wheat. These tests were made both in the field and in the greenhouse. In the greenhouse, plantings were made on December 31, 1921, on both steam-sterilized and unsterilized soil, and notes were taken one month later (see Table III).

TABLE III

COMPARISON OF GERMINATION AND SEEDLING DEVELOPMENT OF BLACK-POINTED AND NORMAL MARQUIS WHEAT KERNELS IN THE GREENHOUSE

Soil treatment	Kind of seed	No. of seeds planted	No. of seeds which germinated	Per cent of seeds which germinated	Mean height of plants, cm.
Sterilized soil	Normal	100	100	100	21.47 ± .10
	Black-pointed	100	89	89	19.54 ± .30
Unsterilized soil	Normal	400	356	89	21.23 ± .14
	Black-pointed	400	336	84	21.17 ± .17

It should be noted that only plump black-pointed kernels were used in these experiments, so that any differences can be attributed more directly to the effect of the organisms carried by such seeds than if shriveled kernels were compared with normal ones. It is evident that the viability of the seed is reduced somewhat by the disease, and on the sterilized soil there was a significant difference in growth, as measured by mean height of tops, but there was no significant difference on unsterilized soil. No particular difference was noted in the amount of root- and foot-rots on the plants in the different series, so it would seem that conditions were not particularly favorable for the development of the fungi in this experiment.

The sample of Marquis wheat used in the field tests germinated rather poorly. Sixty-seven per cent of the apparently normal kernels germinated, while only 50 per cent of the black-pointed ones were viable. Rod rows of one hundred seeds each were planted at two different dates and the plants allowed to develop to maturity. Only 30 per cent of the black-pointed seeds germinated in the first planting as compared with 61 per cent of the normal seeds. Consequently the differences in yield were large. Much less marked differences, however, occurred in the second planting, so it would appear that environmental conditions play an important part in determining the degree of damage resulting from the use of black-pointed kernels for seed. (See Table IV.)

TABLE IV

EFFECT OF BLACK-POINT ON GERMINATION AND YIELD OF MARQUIS WHEAT IN THE FIELD

Date sown	Kind of seed	No. of seeds planted	Per cent germination	Total weight of mature plants, gms.	Total weight of grain, gms.
May 20	Normal	100	61	363.0	64.5
	Black-pointed	100	30	142.0	25.5
May 25	Normal	100	60	148.0	18.0
	Black-pointed	100	51	146.5	17.5

In order to ascertain whether fungi other than *H. sativum,* which were found associated with black-pointed kernels, might not also be responsible for embryo discolorations, inoculations were made on immature wheat heads in the greenhouse and in the field, with several fungi isolated from wheat seeds. As it seemed probable that *Fusaria* and other light-colored species were less likely to cause creosote discolorations, only dematiaceous forms were chosen for these studies.

The cultures used sporulated well on potato dextrose agar and were grown on this medium to obtain inoculum. Wheat heads were inoculated by transferring spores and mycelium from the surface of agar slants to the outer surface of the wheat spikelets. Heads were selected in which the grain was mostly in the milk stage, altho heads in flower and those with only partly formed grain were also inoculated. They were atomized with tap water before and after inoculation. Only the well-developed central spikelets of the heads were inoculated, and counts were made later of only the two outer grains in each spikelet, that is, the largest and best developed seeds. Controls were treated in a similar manner except that no inoculum was applied to them. In the greenhouse experiments, the inoculated plants and controls were placed in moist incubation chambers for forty-eight hours after inoculation and were then placed on greenhouse benches. In the field, the inoculations were made an hour or two before sundown, and the heads were then covered with glassine bags for forty-eight hours.

Table V summarizes the results of greenhouse inoculations made on May 28 and August 25, 1922, and field inoculations made on July 8.

TABLE V

RELATIVE ABILITY OF DIFFERENT FUNGI ISOLATED FROM WHEAT SEEDS TO CAUSE BLACK-POINT OF MARQUIS WHEAT

Fungi	Source of seed from which fungi were obtained	No. of inoculated seeds examined		No. of inoculated seeds which developed black-point		Per cent of inoculated seeds which developed black-point	
		Greenhouse	Field	Greenhouse	Field	Greenhouse	Field
Helminthosporium sativum	Buffalo, Okla.	43	39	23	8	53.5	20.5
Helminthosporium N	St. Paul, Minn.	26	59	11	8	42.3	13.6
Helminthosporium M	St. Paul, Minn.	67	56	16	5	23.9	8.9
Stemphylium parasiticum	Eureka, Calif.	43	75	10	7	23.3	9.3
Stemphylium sp.	Unknown	22	28	0	0	0	0
Torula sp.	Indian Head, Sask.	15	65	0	1	0	1.5
Alternaria sp.	Boerne, Texas	46	83	0	1	0	1.2
Cladosporium sp.	Beaver Lodge, Alta.	15	26	1	0	0	0
Control		59	78	0	0	0	0

As indicated in Table V, four cultures, representing at least two genera and four species, caused black-point both in the greenhouse and in the field. The pathogenicity of each was proved by following out the rules of proof. All three cultures of *Helminthosporium* attacked the glumes as well as the seed. *Helminthosporium N* and *Helminthosporium M* each produced a brown discoloration of the glumes very similar to that caused by *H. sativum* and both were recovered therefrom. Each also caused floret sterility when heads in the flowering stage were inoculated. Their relative virulence as root-rotting organisms will be discussed later. While these results again indicate that *H. sativum* probably is the principal cause of black-point, they also show that other species (31) can cause it (Plate II, Fig. 1). *Stemphylium parasiticum* (Thüm.) Elliot is probably unimportant, as it was isolated only once by the writer. The positive results with *Torula* and *Alternaria* in the field were inconclusive, as only one black-pointed kernel developed in either case, and neither fungus was recovered. The fact that greenhouse inoculations were unsuccessful also indicates that these cultures are nonpathogenic. Two other strains of Alternaria were also tried but with the same results. *Stemphylium parasiticum* was isolated from the one black-pointed kernel which developed in a head inoculated with *Cladosporium,* so there evidently had been accidental contamination with that fungus.

The fact that a lower percentage of successful infections was obtained in the field than in the greenhouse can well be attributed to the dry weather and consequent unfavorable conditions for infection.

SOIL FUNGI

Waksman (85) gives a good historical review and an extensive bibliography of the work on soil fungi previous to 1916. In an examination of eight different soils, more than 100 distinct species of fungi belonging to 31 genera, were isolated. The genera most commonly found were *Penicillium, Mucor, Aspergillus, Trichoderma, Cladosporium, Fusarium, Cephalosporium, Rhizopus, Zygorhynchus, Acrostalagmus, Alternaria,* and *Verticillium.* It is pointed out that Köning found 7 of these 12 genera; Dale, 10; Jensen, 9; Goddard, 9; and McLean and Wilson, 8, indicating their general distribution in the soil. *Mucor, Penicillium, Aspergillus,* and *Trichoderma* were found by all six investigators (including Waksman), showing that these are probably common in most soils. It is stated that more than 50 genera of fungi have been found in the soil and that the largest numbers occur within the upper four inches.

Beckwith's (3) work is of particular interest here, as he investigated the fungous flora of wheat-sick soils. The following genera were found in the soil of a plot on the North Dakota Agricultural Experiment Station farm, which had been cropped to wheat continuously for forty years: *Colletotrichum* (two species), *Macrosporium, Alternaria, Spicaria, Verticillium, Rhaphalomyces, Cephalothecium,* and *Helminthosporium.* Five of these, namely, *Fusarium, Colletotrichum, Macrosporium, Alternaria,* and *Helminthosporium,* are said to be pathogenic to wheat. These fungi were seldom found in virgin soil. It is considered, therefore, that this is additional evidence that part of the deterioration in wheat yields of the Northwest may be due to soil fungi.

Bolley (7) presents the results of another series of cultures made by Beckwith from the soil of some wheat fertilizer plots at the North Dakota Experiment Station. These were made at intervals from February to July, 1911. In February *Alternaria, Colletotrichum, Fusarium,* and *Verticillium* were isolated, while in June only the first three were obtained. It is interesting to note that *Helminthosporium* was not obtained from these soils.

In the isolations made by the writer, *Helminthosporium* was never obtained directly from the soil. It was isolated, however, from the roots of sterile seedlings sown on sick soil. Several species of *Fusarium* were found rather frequently in the soil, but only a few were identified. *Fusarium moniliforme* Sheldon was obtained directly from the soil of a continuous wheat plot at University Farm, St. Paul, and also from a soil secured from Brandon, Manitoba. It also was isolated from the roots of sterile wheat seedlings planted on sick soil. *Fusarium betae* (Desm.) Sacc. (identification by Dr. Sherbakoff) was also obtained from the Brandon soil. A *Fusarium* species, placed by Dr. Sherbakoff in the section Elegans but not determined specifically, was isolated from the roots of sterile seedlings grown on a continuous wheat plot at St. Paul. Green species of *Trichoderma* occurred quite commonly in cultures from the soil, and a species of *Phoma* was obtained several times from soil at University Farm. *Colletotrichum* was not isolated from any of the soils used, altho from Beckwith's results it was expected. Species of *Penicillium, Aspergillus,* and *Mucor* were rather common. Species of *Rhizopus, Alternaria, Cladosporium, Chaetomium, Cephalosporium, Stilbella, Acrostalagmus,* several non-sporulating forms, some which produced only chlamydospores, and several which were not identified, also were found. As the principal object was to find pathogenic forms, time did not allow a careful study of many interesting non-pathogenic species.

FUNGI FROM MISCELLANEOUS SOURCES

Several fungi were isolated from root and foot lesions of wheat and other cereals, and some were obtained from other sources. Many of the same species and genera obtained from the seed and from the soil are also represented here. A few different ones, however, were secured. *Colletotrichum graminicolum* (Ces.) Wilson was isolated from the foot of a mature wheat plant. *Pleospora sp.*, probably *P. trichostoma* (Fr.) Wint., which proved to be the perfect stage of an *Alternaria,* was isolated from old wheat straw. *Helminthosporium gramineum* (Rab.) Erik. was obtained from a single spore from a typical stripe lesion on a barley leaf, while a culture of *Helminthosporium teres* Sacc. was obtained in a similar manner from a typical net-blotch lesion on barley, and a species of *Helminthosporium* apparently differing from any previously described species was obtained from a diseased wheat root. *Piricularia grisea* (Cke.) Sacc. was isolated from a leaf-spot on a seedling millet leaf. In addition, several cultures were obtained from other workers for which grateful acknowledgment is herewith made, e.g., *Helminthosporium sp.* (of the general *H. sativum* type) from J. J. Christensen (originally from Dr. F. L. Stevens); herbarium cultures of *Fusarium culmorum* (W.G.Sm.) Sacc. and *Fusarium lini* Bolley from Dr. Louise Dosdall; and a *Fusarium moniliforme* Sheldon culture from Dr. W. D. Valleau.

PRELIMINARY PATHOGENICITY STUDIES

In order to obtain a preliminary indication of the parasitism of the different cultures, essentially the same method as that used by Stakman (76) was employed. Sterile Marquis wheat seedlings were prepared as previously described and planted in tubes of nutrient agar. Modified Sach's solution or the three-salt solution of Livingston and Tottingham,

R_8C_1, (47) plus 2 per cent agar, proved equally satisfactory. Equal quantities of this medium were placed in each of several large test tubes, and these were then plugged and sterilized. A 1 by 8 inch or a 1 by 12 inch tube was usually used, but occasionally smaller ones were employed. The medium was tubed when the seedlings were ready to be transferred, so that the agar would still be comparatively soft. A single seedling was planted in each tube by means of sterile forceps. The seedlings were then arranged with a sterile platinum needle so that the rootlets penetrated into the soft agar. They were then inoculated with different fungi. This was accomplished by placing a bit of mycelium from the surface of an agar slant of each culture on the surface of the agar at the junction of the seed and roots. Several tubes of each series were left uninoculated. The tubes were inserted in jars of sand so that the roots were in comparative darkness, and the jars were then placed near a window in the laboratory. The final notes were usually taken after about three weeks. The degree of parasitism of the different fungi was then judged by their effect on the development of the seedlings, but particular attention was given to evidences of root parasitism as judged by stunting, deformity, discoloration, and other conditions of the roots as compared with the white uninjured roots of the controls. The results of these preliminary tests are summarized in Table VI (see also Plate I).

On the basis of these trials it was possible to reject many cultures, so far as further pathogenicity tests were concerned. It was considered that any cultures marked "—" did not merit further trial except for comparative purposes. It was also considered that most of the weak pathogenes could be discarded without danger of eliminating any which would be likely to prove destructive in the field. The fact that such well known pathogenes as *Gibberella saubinetii* and *Helminthosporium sativum* always parasitized the plants, whereas such saprophytes as *Cladosporium*, *Cephalothecium*, and *Chaetomium* did not, indicates that these tests at least gave a rough indication of the relative pathogenicity of the different fungi.

TABLE VI

SUMMARY OF RESULTS OF INOCULATING ROOTS OF MARQUIS WHEAT SEEDLINGS GROWING IN AGAR, WITH DIFFERENT FUNGI

Fungus	Source	No. of cultures tested	Degree of parasitism*		
			+	±	—
Alternaria spp.	Seed	47	6	35	6
Stemphylium parasiticum	"	1	0	1	0
Stemphylium sp.	"	1	0	0	1
Helminthosporium sativum	"	11	11	0	0
Helminthosporium N	"	3	2	1	0
Helminthosporium M	"	3	1	2	0
Torula sp.	"	2	0	0	2
Cladosporium sp.	"	2	0	0	2
Gibberella saubinetii	"	3	3	0	0

TABLE VI—*Continued*

Fungus	Source	No. of cultures tested	Degree of parasitism*		
			+	±	—
Fusarium moniliforme	Seed	4	2	2	0
Fusarium spp.	“	8	4	4	0
Cephalothecium roseum	“	2	0	0	2
Aspergillus spp.	“	6	1	2	3
Penicillium spp.	“	4	0	1	3
Acrostalagmus spp.	“	3	0	2	1
Chaetomium sp.	“	1	0	0	1
Trichoderma sp.	“	1	0	1	0
Epicoccum sp.	“	2	0	0	2
Other fungi	“	15	0	9	6
Fusarium moniliforme	Soil (direct)	2	2	0	0
Fusarium betae	“ “	1	1	0	0
Fusarium spp.	“ “	15	10	4	1
Trichoderma spp.	“ “	7	3	4	0
Phoma sp.	“ “	2	1	1	0
Acrostalagmus sp.	“ “	1	0	1	0
Cephalosporium sp.	“ “	2	0	2	0
Stilbella sp.	“ “	1	0	0	1
Rhizopus spp.	“ “	8	0	0	8
Mucor spp.	“ “	5	0	0	5
Penicillium spp.	“ “	7	0	3	4
Aspergillus spp.	“ “	9	0	4	5
Cladosporium sp.	“ “	3	0	0	3
Alternaria sp.	“ “	2	0	2	0
Chaetomium sp.	“ “	2	0	0	2
Other fungi	“ “	26	0	20	6
Helminthosporium sativum	Soil (on roots)	1	1	0	0
Fusarium moniliforme	“ “ “	1	1	0	0
Fusarium spp.	“ “ “	6	4	1	1
Fusarium sp. (Elegans section)	“ “ “	1	1	0	0
Rhizopus sp.	“ “ “	1	0	0	1
Cephalosporium sp.	“ “ “	1	0	1	0
Other fungi	“ “ “	4	0	0	4
Helminthosporium sativum	Wheat (foot and roots)	6	6	0	0
Helminthosporium pedicellatum n.sp.	Wheat (roots)	1	0	1	0
Fusarium sp. (Elegans section)	“ “	1	1	0	0
Fusarium spp.	“ “	5	3	2	0
Gibberella saubinetii	“ “	3	3	0	0
Colletotrichum graminicolum	“ “	1	1	0	0
Acrostalagmus sp.	“ “	3	1	2	0
Aspergillus sp.	“ “	1	0	0	1
Trichoderma sp.	“ “	1	0	1	0
Cephalosporium sp.	“ “	1	0	1	0
Chaetomium sp.	“ “	1	0	0	1
Pleospora sp.	“ “	1	0	1	0
Penicillium sp.	“ “	1	0	0	1
Rhizoctonia sp.	“ “	2	2	0	0
Other fungi	“ “	22	0	15	7
Fusarium lini	(herbarium)	1	1	0	0
Fusarium culmorum	“	1	0	1	0
Helminthosporium sativum	(Stevens)	1	1	0	0
Gibberella saubinetii	(rye)	1	1	0	0
Fusarium spp	(miscellaneous)	4	2	1	1
Piricularia grisea	(millet)	1	0	0	1
Other fungi	(miscellaneous)	15	0	8	7
Totals		301	76	136	89

* + Parasitic. ± Weakly parasitic. — Non-parasitic.

PATHOGENICITY TESTS IN THE GREENHOUSE

The selected cultures were now given a thoro test in inoculated soil in the greenhouse. Each fungus was tested by inoculating the soil in four 4-inch pots with a pure culture, and planting each with twenty-five seeds of Marquis wheat, so that each series consisted of a test of one hundred seeds. The seeds were surface sterilized as previously described. The soil used was a mixture of two parts garden loam and one part sand. This was steamed usually for three hours on each of two successive days. The inoculum was grown in small Erlenmeyer flasks, on sterilized wheat seed soaked with water. All the fungi grew well on this medium and it was afterwards easily broken up and distributed through the soil. As nearly an equal quantity as possible of inoculum was added to each of the pots. The controls were treated in a similar manner except that the sterilized uninoculated medium was introduced into the soil instead of the inoculated medium. The different pots of the different series were placed some distance apart on greenhouse benches in order to prevent the spread of inoculum from one series to another. Notes were taken after about thirty days. The contents of the pots were removed and the soil was washed away from the roots in running water. Notes were then taken on both roots and tops. The number of seedlings that survived was recorded, and the number of these which showed root- or foot-rot and the severity of each was noted. Relative growth was measured by taking the total dry weight of the tops and in some instances their mean height. The former was considered the more reliable, however, and was used throughout, while the latter was frequently omitted in order to reduce the amount of work. These tests were continued from July 5, 1922, to March 11, 1923, and the results are presented in Table VII. Plate III, Figure 2, shows a typical control series compared with one in which *Fusarium moniliforme* was used as the inoculum.

TABLE VII

RESULTS OF INOCULATING MARQUIS WHEAT WITH DIFFERENT FUNGI

Series No.	Fungus	Length of test in days	Source of culture*	Stunted seedlings†‡	Seedlings with root-rot†‡	Seedlings with foot-rot†‡	Mean height, cms.	Total dry weight of tops, gms.	Observations
		7/5-8/5							
1	Fusarium moniliforme	31	Seed	......	$57^{h}/57$	$55^{l}/57$	8.8	0.76	10 plants dead
2	Fusarium sp.	"	"	......	$69^{l}/73$	$44^{l}/73$	41.9	6.45	
3	Helminthosporium gramineum	"	Barley leaf	......	$38^{l}/76$	$1^{tr}/76$	41.7	6.89	
4	Unknown (formed chlamydospores only)	"	Soil	......	$42^{l}/60$	$3^{tr}/60$	40.7	6.12	
	Control	"		......	$36^{l}/68$	$4^{tr}/68$	38.0	5.75	
		7/5-8/7							
5	Trichoderma sp.	33	"	......	$71^{l}/74$	$4^{tr}/74$	37.7	5.24	
6	Fusarium sp.	"	Seed	......	$7^{tr}/75$	0/75	41.1	8.09	
7	Fusarium sp.	"	Soil	......	$46^{l}/74$	0/74	42.2	6.71	
8	Fusarium sp.	"	"	......	$38^{l}/65$	0/65	45.5	6.40	
9	Unknown (formed chlamydospores only)	"	"	......	$3^{l}/70$	0/70	38.4	7.38	
	Control	"		......	$22^{tr}/56$	0/56	35.8	5.74	
		7/25-8/25							
10	Phoma sp.	31	Soil	1/62	$39^{l}/62$	$15^{tr}/62$	...	6.17	
11	Helminthosporium sativum	"	Roots	7/53	$53^{m}/53$	$20^{l}/53$	...	4.42	
12	" "	"	Seed	9/62	$62^{m}/62$	$30^{l}/62$	...	6.29	
13	Helminthosporium M. Strain 1	"	"	7/58	$57^{m}/58$	0/58	...	6.64	
14	Helminthosporium N	"	"	5/37	$37^{m}/37$	$3^{tr}/37$	...	4.14	
15	Helminthosporium sativum	"	Furnished by F. L. Stevens	8/48	$48^{m}/48$	$6^{m}/48$	...	5.92	
	Control	"		7/49	$21^{tr}/49$	$3^{tr}/49$	...	4.59	
		7/31-8/31							
16	Gibberella saubinetii	31	Seed	3/3	$2^{h}/3$	$2^{tr}/3$	6.0	0.01	2 plants dead
17	Helminthosporium sativum	"	"	8/36	$36^{h}/36$	......	37.3	3.59	1 plant dead
18	Trichoderma sp.	"	Soil	2/51	$13^{tr}/51$	$2^{tr}/51$	...	6.65	
19	Alternaria sp.	"	Seed	3/54	$11^{tr}/54$	$3^{tr}/54$	...	7.57	
20	Rhizoctonia	"	Roots	1/52	$20^{tr}/52$	$5^{tr}/52$	...	7.13	
	Control	"		7/79	$14^{tr}/79$	0/79	40.4	7.53	

TABLE VII—*Continued*

RESULTS OF INOCULATING MARQUIS WHEAT WITH DIFFERENT FUNGI

Series No.	Fungus	Length of test in days	Source of culture*	Stunted seedlings†‡	Seedlings with root-rot†‡	Seedlings with foot-rot†‡	Mean height, cms.	Total dry weight of tops, gms.	Observations
		7/29-9/1							
21	Trichoderma sp.	34	Seed	4/55	30tr/55	$11^{tr}/55$	...	6.83	
22	Helminthosporium teres	"	Barley leaf	4/67	$7^{tr}/67$	$2^{tr}/67$	...	9.74	
23	Aspergillus niger	"	Seed	5/52	$31^{l}/52$	$1^{tr}/52$	...	5.98	
24	Unknown (formed chlamydospores only)	"	Soil	2/42	$10^{tr}/42$	$2^{tr}/42$	...	5.65	
25	Fusarium sp.	"	Roots	4/56	$24^{l}/56$	$0^{tr}/56$	...	6.29	
26	Unknown (formed chlamydospores only)	"	Soil	3/55	$9^{tr}/55$	0/55	...	5.63	
27	Fusarium sp.	"	"	7/51	$27^{l}/51$	$9^{tr}/51$	...	5.00	
	Control	"		6/76	$11^{tr}/76$	0/76	40.7	8.21	
		7/31-9/5							
28	Gibberella saubinetii	36	Roots	6/28	$27^{l}/28$	0/28	41.9	3.32	
29	Fusarium sp. (Elegans section)	"	Soil (on roots)	1/6	$6^{m}/6$	0/6	41.4	0.49	
30	Gibberella saubinetii	"	Roots	6/34	$30^{m}/34$	$8^{l}/34$	36.7	1.22	1 plant dead
31	Fusarium lini	"	Herbarium	6/49	$42^{l}/49$	0/49	37.5	4.74	
32	Fusarium sp.	"	Roots	1/47	$15^{l}/47$	0/47	40.5	4.39	
33	Fusarium sp.	"	Barley foot	2/63	$63^{tr}/63$	0/63	34.7	4.48	
34	Fusarium sp.	"	Soil	4/60	$8^{tr}/60$	0/60	...	6.72	
35	Fusarium sp.	"	Roots	4/46	$29^{tr}/46$	$1^{tr}/46$	...	4.34	
36	Fusarium sp.	"	Soil	3/59	$26^{tr}/59$	0/59	...	5.53	
	Control	"		4/67	$5^{tr}/67$	0/67	42.4	6.48	
		8/11-9/12							
37	Helminthosporium M. Strain IV	32	Millet leaf	2/20	$20^{m}/20$	0/20	28.1	1.13	
38	Phoma sp.	"	Soil	0/40	$31^{l}/40$	$2^{tr}/40$	37.7	3.69	
39	Alternaria sp.	"	Seed	3/53	$14^{l}/53$	0/53	...	4.07	
40	Fusarium moniliforme	"	"	13/25	$25^{h}/25$	$6^{l}/25$	24.1	1.16	2 plants dead
41	Fusarium sp.	"	Foot	15/72	$51^{l}/72$	0/72	29.0	3.69	
42	Alternaria sp.	"	Seed	4/79	$17^{tr}/79$	0/79	...	5.07	
43	Alternaria sp.	"	Seed	3/72	$16^{tr}/72$	$1^{tr}/72$	...	5.41	
44	Alternaria sp.	"	"	1/77	$31^{l}/77$	$3^{tr}/77$	...	4.79	
	Control	"		3/64	$3^{tr}/64$	0/64	36.7	5.41	

TABLE VII—*Continued*

RESULTS OF INOCULATING MARQUIS WHEAT WITH DIFFERENT FUNGI

Series No.	Fungus	Length of test in days	Source of culture*	Stunted seedlings†‡	Seedlings with root-rot†‡	Seedlings with foot-rot†‡	Mean height, cms.	Total dry weight of tops, gms.	Observations
		8/17-9/18							
45	Fusarium sp. (Elegans section)	32	Foot	5/18	$12^{1}/18$	0/18	23.7	0.77	
46	Fusarium moniliforme	"	Soil	50/60	$60^{h}/60$	$2^{tr}/60$	20.3	0.90	6 plants dead
47	Fusarium moniliforme	"	Seed	13/31	$31^{m}/31$	$1^{tr}/31$	23.1	1.07	1 plant dead
48	Acrostalagmus sp.	"	Roots	9/77	$55^{1}/77$	0/77	...	3.91	
49	Stemphylium parasiticum	"	Seed	8/77	$31^{tr}/77$	2/77	...	5.94	
50	Pink fungus (no spores)	"	Roots	4/35	$23^{1}/35$	$7^{tr}/35$	35.1	2.62	2 plants dead
	Control	"		4/62	$10^{tr}/62$	$2^{tr}/62$	34.2	4.25	
		8/28-9/30							
51	Chaetomium sp.	33	Seed	3/92	$13^{1}/92$	0/92	...	3.44	
52	Fusarium sp.	"	"	5/84	$8^{1}/84$	0/84	...	3.64	
53	Gibberella saubinetii	"	Seed	4/31	$24^{m}/31$	0/31	24.3	1.19	7 plants dead
54	Alternaria	"	"	7/75	$33^{1}/75$	0/75	...	2.49	
55	Helminthosporium sativum	"	Roots	5/58	$52^{1}/58$	29/58	...	3.66	
56	Gibberella saubinetii	"	Seed	6/15	$12^{m}/15$	$8^{m}/15$	16.8	0.33	3 plants dead
57	Gibberella saubinetii	"	Roots	17/23	$23^{m}/23$	$16^{1}/23$	13.9	0.50	13 plants dead
	Control	"		8/85	$19^{tr}/85$	0/85	29.7	3.68	
		9/12-10/15							
58	Trichoderma	33	Soil	3/85	$27^{tr}/85$	0/85	...	4.14	1 plant dead
59	Acrostalagmus	"	Roots	13/88	$36^{1}/88$	0/88	...	3.69	" " "
60	Colletotrichum graminicolum	"	Foot	6/84	$45^{1}/84$	1/84	...	4.16	
61	Fusarium sp.	"	Rye foot	17/62	$41^{1}/62$	0/62	...	2.31	" " "
62	Fusarium sp.	"	Soil	3/90	$7^{tr}/90$	0/90	...	5.20	
63	Fusarium sp.	"	Roots	8/80	$8^{tr}/80$	$3^{tr}/80$	...	4.30	
	Control	"		11/74	$26^{1}/74$	0/74	...	3.21	
		10/14-11/14							
64	Helminthosporium M. Strain I	31	Seed	60/68	$68^{m}/68$	$36^{1}/68$	9.5	0.44	Tops attacked by mice
65	Helminthosporium M. Strain IV	"	Millet leaf	8/84	$84^{1}/84$	$10^{1}/84$	...	...	Tops attacked by mice

TABLE VII—*Continued*

RESULTS OF INOCULATING MARQUIS WHEAT WITH DIFFERENT FUNGI

Series No.	Fungus	Length of test in days	Source of culture*	Stunted seedlings†‡	Seedlings with root-rot†‡	Seedlings with foot-rot†‡	Mean height, cms.	Total dry weight of tops, gms.	Observations
66	Helminthosporium M. Strain II	31	Seed	4/76	$76^{tr}/76$	0/76	...	...	Tops attacked by mice
67	Helminthosporium M. Strain III	"	"	30/94	$56^{tr}/94$	0/94	...	1.94	Tops attacked by mice
68	Helminthosporium pedicellatum n. sp.	"	Roots	8/72	$42^{tr}/72$	$2^{tr}/72$	...	1.74	Tops attacked by mice
69	Cephalosporium sp.	"	"	10/84	$26^{tr}/84$	$0^{tr}/84$	...	1.96	Tops attacked by mice
70	Cephalosporium sp.	"	Soil	12/64	$8^{tr}/64$	0/64	...	1.50	Tops attacked by mice
	Control	"		16/72	$28^{tr}/72$	0/72	26.5	1.60	Tops attacked by mice
		1/5-2/12							
71	Acrostalagmus sp.	38	Soil	17/90	$65^{l}/90$	$19^{tr}/90$	25.1	3.72	
72	Fusarium sp.	"	"	3/93	$93^{tr}/93$	$9^{tr}/93$	31.0	5.98	
73	Acrostalagmus sp.	"	Roots	31/92	$92^{m}/92$	$20^{tr}/92$	22.2	3.80	
74	Fusarium sp.	"	Soil	8/88	$23^{l}/88$	$5^{tr}/88$	29.3	5.44	
75	Fusarium sp.	"	Roots	6/76	$10^{tr}/76$	$3^{tr}/76$	25.7	...	
	Control	"		11/91	0/91	0/91	27.8	5.03	
		1/27-3/11							
76	Cephalosporium sp.	43	Soil	7/97	$32^{tr}/97$	0/97	33.0	9.03	
77	Fusarium sp.	"	"	0/94	$13^{tr}/94$	0/94	37.4	9.06	
78	Fusarium betae	"	"	6/98	$34^{tr}/98$	0/98	31.9	7.34	
	Control	"		1/97	0/97	0/97	32.5	6.84	

* Plant part sources refer to wheat where not otherwise specified.

† The denominator of the fractions represents the total number of seeds which produced plants. As 100 seeds were sown in each series, the number also indicates the percentage of seeds from which plants developed. The numerator represents the number of diseased plants, including those which were stunted or affected with root- or foot-rots.

‡ ^{h} = heavy. ^{m} = moderately heavy. ^{l} = light. ^{tr} = trace.

As an abundance of inoculum was used in these tests, it would seem that any virulent pathogenes would have a pronounced effect on the growth of the plants. None, however, except certain species of *Fusarium* and *Helminthosporium* was very virulent. Several other fungi did attack the roots, but in general not severely enough to interfere seriously with the growth of the plants. It scarcely seems probable that they would do much damage in the field, where the inoculum would be less plentiful. Several cultures which were marked "+" in the preliminary tests were either only slightly pathogenic or non-pathogenic in the greenhouse, e. g., numerous species of *Fusarium*. It will be noted that the control plants usually developed some root-rot also. This apparently was because the medium added to the soil formed a suitable substratum for the growth of any fungi which happened to be washed down from the surface of the soil. In the inoculated pots, on the other hand, the medium from the beginning of the experiment would be thoroly permeated with the mycelium of one fungus and hence others would not readily grow there.

DISCUSSION OF DIFFERENT FUNGI AND THEIR EFFECT ON THE HOST

FUSARIUM SPP.

Fusarium graminearum, Schwabe (*Gibberella saubinetii* (Mont.) Sacc.).—This is a well-known parasite of wheat and other cereals (73, 1, 2, 36, 25, 53). It was the most virulent of any of the fungi studied. In most of the trials with this organism in the greenhouse, all or nearly all the seedlings were killed before they emerged from the soil. The virulence of different cultures varied somewhat. Two cultures, one isolated from wheat seed obtained from the Argentine, and another from seed from North Dakota, were particularly destructive. (Table VII—series 56 and 16.) The roots of surviving seedlings were usually stunted and badly rotted, altho occasionally one would develop a few normal roots and apparently recover. The affected roots were usually light brown to reddish brown in color. In the roots examined, the central cylinder usually was destroyed first and the cortex later. The mycelium was intracellular in the stele. All stages of decay were noted, from a slight browning of a few cell walls to a general disintegration. Some of the cells were frequently completely filled with a brown mass of material which probably consisted partly of mycelium and partly of disintegration products of the decaying cell walls. In the cortex the mycelium was both intra- and intercellular. There is little doubt that the importance of this fungus in the field as a cause of seedling blight is in large measure due to its destructiveness on the roots.

Fusarium culmorum (W. G. Sm.) Sacc.—While this fungus is frequently confused with *Fusarium graminearum* Schwabe, it is undoubtedly a distinct species (89). Its ability to cause root-rot of wheat was carefully studied by Stakman (76), who found it very destructive on all parts of the roots. She observed that the vascular tissue was usually attacked first, after which the hyphae spread out through the cortex. In the stele the hyphae were found inside the cells, whereas in the cortex they were mostly intercellular. The writer did not carefully study the relation of this organism to the host. A herbarium culture of the fungus was used in preliminary pathogenicity tests but it was only weakly parasitic and hence was not studied further. Possibly the virulence of the culture had been diminished by long-continued growth on artificial media.

Fusarium moniliforme Sheldon.—Sheldon (69) first found *F. moniliforme* in 1903 on corn in Nebraska, and described it as a new species. A similar fungus found on corn was described by Saccardo (66) as *Oospora verticilloides* Sacc. This in all probability was *F. moniliforme*, but Saccardo failed to observe the macroconidia. Chen (12) isolated a fungus corresponding to Saccardo's *Oospora verticilloides,* but states that if macroconidia were found it would be necessary to describe it as *F. moniliforme* Sheldon. During the last few years, the relation of *F. moniliforme* to foot- and root- and kernel rots of corn has been studied rather extensively in this country. Valleau (84) summarizes the literature on this subject up to 1920. Manns and Adams (48, 49) more recently present further data on its distribution, importance, and prevalence. In a later paper (50) they discuss this fungus as an internal parasite of seed corn. The only previous mention of the occurrence of *F. moniliforme* on wheat that has come to the writer's attention is that of Sherbakoff (71) who states that he found it on wheat seed, altho not often.

As has been mentioned, the writer isolated *Fusarium moniliforme* from wheat seed, wheat roots, and wheat-sick soil. The identity of the fungus, however, was not determined until after it had been tested in the greenhouse for the first time (Table VII, Series 1). The results of that test were so pronounced that an attempt was immediately made to identify the fungus.

It was not readily identified at first,, because the culture examined was growing on potato dextrose agar, and on that medium macroconidia were rare. Both macroconidia and microconidia were abundant on the sterilized wheat seed medium, however. These agreed in all essential characters with Sheldon's description and figures of *F. moniliforme*. In order to prove, however, that the two spore forms belonged to the same fungus, six single spore cultures were started from microconidia, and six from macroconidia. In every instance both types of conidia were produced by the single spore cultures when grown on sterilized wheat seed. In subsequent work only single spore cultures were used.

It was thought that strains of this fungus from different sources might be different. Valleau (84), for instance, found at least two and possibly three distinct strains on corn. Sherbakoff (71) also observed differences in different cultures answering the general description of this species, and proposed a new section of the genus *Fusarium,* namely, Moniliform, to include those forms producing their microconidia in chains.

The writer compared three of his cultures and one obtained from Dr. Valleau on the following media recommended by Sherbakoff (70): a hard oat agar (without glucose), a stem and tuber plug (beans and potatoes), and a potato agar with 5 per cent glucose. For convenience the cultures used will be designated as follows:

Strain number	Isolated from
I	Wheat seed from Missouri
II	Soil from St. Paul
III	Wheat roots from St. Paul
IV	Corn (?) from Kentucky (Dr. Valleau)

Marked differences between the strains appeared only on the potato agar. Strains II and III reacted similarly on this medium. Both caused the entire substratum to become deep reddish purple and both developed a light salmon-pink aerial mycelium. Strain I produced a similar growth on the surface of the agar but gave a purplish tint only near the surface of the substratum. Strain IV, on the other hand, failed to change the color of the substratum and produced practically white aerial mycelium. When the same strains were grown on sterilized wheat seed, I, II, and III produced macroconidia abundantly, but IV produced comparatively few in three tests made at different times. These results indicate that IV is probably distinct from I, II, and III, that II and III are very similar if not identical and differ only slightly from I.

It was considered that it might be possible to distinguish the strains on the basis of conidial length. An insufficient number of macroconidia was produced by Strain IV to make such measurements possible, hence Strains I and III were chosen for comparison. The measurements were necessarily made on conidia produced on one culture medium only, namely, sterilized wheat seed. Of course single spore cultures of the two strains were used and these were started at the same time on media prepared in the same way. The measurements of the mean length of the macroconidia in the different septation classes follow.

TABLE VIII

Comparison of Conidial Lengths of Two Strains of *F. moniliforme*

Septation classes	Strain I—culture 48 days old			Strain III—culture 51 days old		
	Per cent of spores found	Length, microns	No. measured	Per cent of spores found	Length, microns	No. measured
1-septate	15	24.20	12	20	20.20	20
2-septate	8	30.30	9	4	25.60	4
3-septate	64	39.25 ± 0.39	100	71	38.02 ± 0.32	100
4-septate	8	42.90	15	3	43.10	3
5-septate	4	45.50	13	2	45.30	2
6-septate	1	49.20	2			

It is evident that only the 3-septate classes can be compared reliably, as an insufficient number of spores was found in the other septation classes. Moreover, since 3-septate spores are most typical of *F. moniliforme,* they would naturally be chosen as a basis for comparison. In this case the difference between the mean lengths of the 3-septate macroconidia of Strain I and Strain III is probably not significant, as it is less than three times the probable error of the difference.

It was found that Strains I, II, and III were equally virulent on wheat, while Strain IV was much weaker. Comparative data for Strains III and IV are given in Table IX and in Plate III, Figure 1. Series similar to those reported in Table VII were used.

TABLE IX

Comparison of Relative Virulence of Two Strains of *F. moniliforme* on Marquis Wheat

Strain	Length of test, days	Source of culture	Stunted seedlings	Seedlings with root-rot*	Seedlings with foot-rot	Mean height, cms.	Dry weight, gms.
III	38	Wheat roots	22/22	$22^{h}/22$	$12^{l}/22$	9.14	0.29
IV	38	Corn	18/64	$54^{l}/64$	$45^{tr}/64$	21.99	1.83
Control	38	....	11/91	0/91	0/91	27.81	5.03

* ^{h}=heavy, ^{l}=light, ^{tr}=trace.

Like results were obtained from two other similar tests. In one of these the inoculum was grown on sterilized soil to which 5 grams of cornmeal per 100 grams of soil had been added. The same relation was maintained, however, in respect to the relative pathogenicity of the two strains regardless of the kind of inoculum used, but the injury was of a somewhat lesser degree in the pots receiving the soil inoculum than in those receiving the seed inoculum, owing apparently to a less abundant growth of the fungus in the former. These results again indicate that Strain IV is different from Strains I, II, and III.[6]

The different strains of *Fusarium moniliforme* isolated by the writer were clearly pathogenic to wheat roots. The roots of seedling wheat plants were badly rotted when grown in inoculated agar, nutrient solutions, rag-doll germinators, and soil. The rotted roots were often badly stunted, especially in the inoculated soil (Plate IV). The tops of the diseased seedlings also were usually badly stunted. Both the stele and the cortex were attacked in the diseased roots examined. The former often showed indications of rotting before the latter. Both eventually became thoroly riddled with mycelium and then disintegrated. (Plate IX, Figs. 5 and 6.) The rules of proof were, of course, carried out. The foot of the plant, especially the part above ground, was apparently much less susceptible to attack than the roots. The coleoptiles of the seedlings were often attacked but the stem was usually not attacked until after the plants were greatly weakened by root-rot. Wheat seedlings from two to three weeks old were inoculated on the foot near the surface of the soil, but none developed foot-rot. Six seedlings were wounded before inoculation and four of them died, but it is doubtful if their death was due to the effects of the fungus. On wheat seedlings, therefore, *F. moniliforme* seems to be primarily a root-rotting fungus.

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[6] These strains were sent to Dr. Sherbakoff for identification. He replied that he believed they were all of the *Fusarium moniliforme* species but considered that some of them would prove to be distinct organisms (presumably varieties or physiologic races).

While most of the pathogenicity trials with *F. moniliforme* and with other fungi were made primarily on the seminal roots, a few adventitious roots frequently developed and became diseased before the conclusion of the tests, altho they seemed to be more resistant to most pathogenes than the seminals. Hence seedlings which survived long enough to produce them showed a tendency to recover. This was true even of plants infected with *Gibberella saubinetii*.

Experiments were made to determine whether *F. moniliforme* from wheat would attack other cereals. Table X and Plate V, Figures 1 to 3, show the results of growing wheat, oats, barley, rye, field corn, and sweet corn on soil inoculated with a culture of *F. moniliforme* (Strain I) growing on wheat seed. In these experiments two kinds of checks were used: those to which sterile medium was added and those to which none was added. Wheat, rye, oat, and field corn seedlings in the former type of check grew somewhat less vigorously than those in the latter type (Table X) but these differences were not marked (Plate V). The checks in all cases, however, were much superior to the seedlings in inoculated soil.

Each of the inoculated cereals was attacked by the fungus, which was readily recovered from surface-sterilized portions of the diseased roots, rhizome,[7] or foot of each, and abundant mycelium was found in the diseased tissues. The roots were severely rotted in all cases. Corn was severely attacked at the base of the plants as well, and the rhizomes of the oat plants were often thoroly rotted. The coleoptiles of the other seedlings were frequently discolored, but the stems apparently were invaded only after the plants had become weakened.

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[7] Used in the same sense as Percival (loc. cit. p. 7) used it.

TABLE X

Effect of Inoculating Different Cereals* with *Fusarium moniliforme* from Wheat Seed

Cereal	Soil treatment	Length of test, days	Stunted seedlings†	Seedlings with root-rot	Seedlings with foot-rot	Mean height, cms.	Total dry weight, gms.
Wheat (Marquis)	Control. No medium added	32	0/23	0/23	0/23	28.94	0.77
" "	Control. Medium added	"	2/25	17/25	0/25	27.39	0.74
" "	Inoculated with F.m.	"	15/20	20/20	18/20	12.84	0.23
" "	" " "	"	17/17	17/17	15/17	6.72	0.10
Barley (Improved Manchuria)	Control. No medium added	32	1/25	0/25	0/25	20.94	0.52
" " "	Control. Medium added	"	2/24	1/24	0/24	18.79	0.54
" " "	Inoculated with F.m.	"	16/16	16/16	9/16	7.23	0.19
" " "	" " "	"	21/21	21/21	11/21	6.68	0.19
Rye (Winter Swedish)	Control. No medium added	32	0/25	0/25	0/25	23.22	0.64
" " "	Control. Medium added	"	1/21	12/21	0/21	24.63	0.56
" " "	Inoculated with F.m.	"	16/19	19/19	17/19	9.49	0.21
" " "	" " "	"	12/16	16/16	8/16	11.69	0.19
Oats (Iowa 103-531)	Control. No medium added	32	2/25	0/25	0/25	20.54	0.32
" " "	Control. Medium added	"	5/22	3/22	0/22	18.20	0.27
" " "	Inoculated with F.m.	"	21/21	21/21	21/21	10.72	0.13
" " "	" " "	"	21/25	25/25	25/25	10.43	0.16
Field corn (Minn. No. 13)	Control. No medium added	26	0/10	0/10	0/10	39.2	2.30
" " " " "	Control. Medium added	"	0/9	0/9	0/9	37.2	1.77
" " " " "	Inoculated with F.m.	"	4/4	3/4	3/4	19.9	0.41
" " " " "	" " "	"	9/9	7/9	7/9	12.5	0.44
Sweet corn (Golden Bantam)	Control. No medium added	26	0/8	0/8	0/8	24.8	0.98
" " " "	Control. Medium added	"	0/8	4/8	5/8	24.4	1.23
" " " "	Inoculated with F.m.	"	4/4	1/4	4/4	9.7	0.12
" " " "	" " "	"	3/3	2/3	2/3	7.3	0.09

* Twenty-five seeds per pot of wheat, barley, rye and oats, and ten seeds per pot of corn, were sown.

† The denominator represents the number of seeds which produced plants, and the numerator the number stunted or affected with root- or foot-rot.

It is probable that *F. moniliforme* woud be much less destructive in the field than in these tests, as the amount of inoculum would rarely, if ever, be as abundant under field conditions. In old corn fields, however, *F. moniliforme* must be very prevalent on stubble, old stalks and roots, and even in the soil. It would be expected, therefore, that when wheat or some other cereal was sown on such land its roots would be attacked by this fungus. It is well known that *Gibberella saubinetii* occurs very abundantly in such fields and that wheat following corn is particularly heavily attacked by this fungus. It is possible that *F. moniliforme* may be destructive under similar conditions and that proper crop rotation will help to control it.

Other Fusarium spp.—Two other species of *Fusarium* studied also were decidedly pathogenic to wheat roots (Table VII, Series 29 and 45). Cultures of these were submitted to Dr. Sherbakoff, and he placed them in the section Elegans but has not yet been able to make specific determinations. These species attacked wheat roots in practically the same way as does *Gibberella saubinetti*, but were somewhat less virulent. They usually killed more of the seedlings than did *F. moniliforme.*

Several other species of *Fusarium* were slightly pathogenic on wheat roots in the greenhouse, e.g., *F. lini* (Table VII, Series 31). Many, however, such as *F. betae* (Table VII, Series 78) evidently are unimportant as pathogenes of wheat roots.

HELMINTHOSPORIUM SPP.

Helminthosporium sativum P.K. and B.—The pathogenicity of *H. sativum* on wheat roots has been definitely established by Stakman (75), Stevens (79, 81), Christensen (13), and Dosdall (19). All the strains studied by the writer were parasitic, but one isolated from a wheat seed from Oklahoma was particularly virulent and was used for comparison with other fungi. All the roots of wheat seedlings grown in soil inoculated with this strain were usually attacked. Diseased roots showed general or local browning and often were more or less speckled with minute darker spots over the surface of the rotted portions. Sometimes the rotting involved the whole root but it was often confined to the upper parts or to local areas. Some of the roots were frequently badly stunted by the fungus. The mycelium was found mainly in the cortex. Dark brown lesions frequently occurred on the rhizome, on the foot, and on seedling leaves. Diseased seedlings were usually stunted, altho some of them developed quite normally. In general, however, the stunting was less pronounced and the seedling survival greater than in soil inoculated with pathogenic species of *Fusarium.*

McKinney (55) reported that all the strains of *Helminthosporium* which he isolated from wheat were similar and corresponded morphologically with *H. sativum*. Melchers (83) found at least two species of *Helminthosporium* on wheat but did not state how they differed. Drechsler (20) points out that several species other than *H. sativum* have been found on wheat, e.g., *H. geniculatum*, a small geniculate spored form reported by Palm from Java; *H. tritici* Hennings, a small-spored form differing from the former, collected by Zimmerman in the territory which was formerly German East Africa; a geniculate spored form reported by Stevens (79), in Illinois; and a few small-spored forms reported by Stakman (75), in Minnesota. The writer isolated at least four species (Plate XI) and probably five or more from wheat.

Helminthosporium N.—A *Helminthosporium* species differing from *H. sativum* sufficiently to be regarded as another species was isolated several times from wheat, especially from the seeds. It produced symptoms similar to those caused by *H. sativum* on the roots, foot, leaves, heads, and seeds of wheat, altho all strains tested were less virulent than *H. sativum*. A single spore culture of this organism produced conidia of rather uniform shape but differing considerably in length and number of septations. The conidia resemble those of *Podosporiella verticillata*, O'Gara, a fungus which O'Gara (57) described on germinating wheat seed. No synnemata, however, have been observed in the author's cultures even on wheat and rice, the media on which O'Gara always obtained normal fruiting.[8] The spores are much narrower and more cylindrical than the conidia of *H. sativum*. Data on conidial length, breadth, and number of septations of 100 spores of a single spore culture are compared with similar data for *H. sativum* in Table XI. (See also Plate XI, Figures 1 and 3.) The data on conidial width are also illustrated graphically in Figure 1, page 36. Cultures of the same age grown on sterilized mature wheat heads were used, and care was taken to avoid unconscious selection of the spores measured.

The most pronounced difference is in the width of conidia. This difference is more than forty-two times its probable error. There also is considerable difference in conidial length. It is noteworthy that the conidia of *Helminthosporium N* are shorter than those of *H. sativum*. When the two are examined in the same mount, however, this difference is not very apparent, as the conidia of *Helminthosporium N* look long, probably because they are so much narrower than those of *H. sativum*. No significant difference was found between the mean number of septations of the two, but *H. sativum* was more variable in this respect than *Helminthosporium N*.

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[8] As the production of synnemata seems to take place only under certain conditions, it has seemed advisable to study this fungus further before deciding on its identity. Dr. Drechsler, who examined a culture of the fungus, considered it distinct from *H. sativum* and also noted the similarity of the conidia with those of *Podosporiella verticillata*. He observed light areas at the ends of the spores which were larger than those in *H. sativum* and fuliginous rather than dark olivaceous in color.

TABLE XI

Variations and Constants for Conidial Measurements of *Helminthosporium N* and *Helminthosporium sativum*

a. Conidial lengths in microns

Fungus	Spore classes									Total No.	Constants			
	15	25	35	45	55	65	75	85	95		Mode	Mean	Standard deviation	Coefficient of variability
Helminthosporium N	3	2	6	6	19	24	19	18	3	100	65	64.20 ± 1.21	17.93 + .86	27.92 ± 1.33
Helminthosporium sativum	1	5	3	4	5	15	29	32	6	100	85	71.40 ± 1.21	17.97 ± .86	25.16 ± 1.20

b. Conidial widths in microns

Fungus	Spore classes										Total No.	Constants			
	9	11	13	15	17	19	21	23	25	27		Mode	Mean	Standard deviation	Coefficient of variability
Helminthosporium N	3	8	36	45	5	3	..	..	..	..	100	15	14.00 + .13	1.87 ± .09	13.32 + .64
Helminthosporium sativum	..	1	..	..	3	6	23	13	45	9	100	25	23.26 ± .19	2.75 ± .13	11.82 ± .56

c. Conidial septations

Fungus	Spore classes												Total No.	Constants			
	1	2	3	4	5	6	7	8	9	10	11	12		Mode	Mean	Standard deviation	Coefficient of variability
Helminthosporium N	..	2	5	5	4	9	24	22	21	6	2	..	100	7	7.28 ± .13	1.96 ± .09	26.92 ± 1.28
Helminthosporium sativum	2	4	2	2	8	11	24	18	15	9	4	1	100	7	7.23 ± .15	2.25 ± .11	31.12 ± 1.48

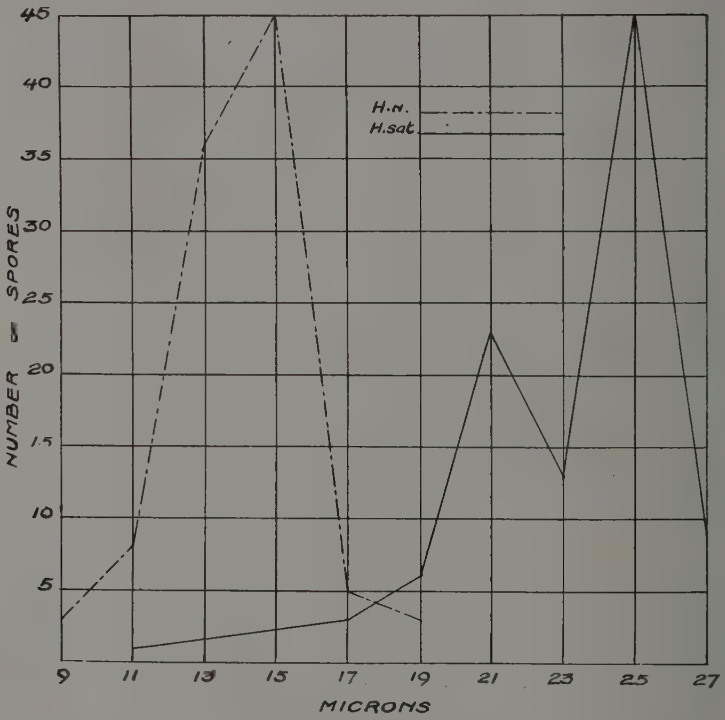

Fig. 1. Relative Conidial Width of Helminthosporium N and H. sativum

Helminthosporium M.—Several similar small-spored strains are included here. These were isolated from several sources, as indicated below. For convenience we shall refer to them by number as follows:

Strain	Isolated from
I	Wheat seed from St. Paul, Minn.
II	" " " Burdette, Kan.
III	" " " Indian Head, Sask.
IV	Millet leaf from Waukegan, Ill.

Two other similar small-spored strains were also isolated, one from wheat roots and one from barley roots, but these were not studied further. The relative pathogenicity, spore dimensions, and reaction on different culture media of Strains I, II, III, and IV, however, were studied in some detail.

The exact identity of these forms is difficult to determine. They apparently may be placed with justification in either of two genera, namely, *Helminthosporium* or *Brachysporium*. They were previously tentatively assigned to the latter genus (31) in order to distinguish them from certain large-spored species of *Helminthosporium* from wheat (Plate XI). If Lindau's (44) suggestion were followed, namely, that *Brachysporium* be reserved for species whose spores are not more than twice as long as they are broad, then three of the above strains would belong in the genus *Helminthosporium* and one in *Brachysporium*. This suggestion, however, has not been followed in the case of many species of *Brachysporium*, e.g., *Brachysporium graminis* Boy. and Jacz. (67) and *Brachysporium trifolii* Kauffman (9). The latter species and also *Helminthosporium inaequalis* Shear (74) have spores which correspond rather closely in shape and size to the conidia of the forms isolated by the writer.

These small-spored cultures were submitted to Dr. Charles Drechsler for identification. He was unable to place them specifically but preferred to refer them to the genus *Helminthosporium* rather than to *Brachysporium*.[9] Stevens (81) also placed several similar small-spored forms isolated from corn, in the genus *Helminthosporium*. In order to avoid confusion, the small-spored forms from wheat, barley, and millet are therefore also referred to this genus in this paper. Two of these strains, namely, III and IV, produced the erect sclerotoid coremia-like bodies in old cultures similar to those described by Shear, for his *H. inaequalis*. It is possible that they are closely related to that fungus, but Dr. Drechsler was of the opinion that they were not identical with it.

In order to compare the cultural characters of the four strains, they were grown on three different media: Oat agar, Czapek's agar, and potato dextrose agar. Cultures from single spores were used in all cases. Duplicate plates of each medium were inoculated with each strain. The plates were inoculated in the center with a small bit of mycelium, and notes were taken on the cultures at the end of the third and sixth days. Invariably, duplicate colonies of the same strain on the same medium were alike. These results are presented in Table XII and Plate VI. Strain I produced an orange pigment on Czapek's agar and on potato dextrose agar, while none of the others did. Strain II could also be readily distinguished from the others on these agars by its uniformly dark, abundantly sporulating colonies. The strains resembled each other most on oat agar, but even on this medium they could be distinguished. Strains III and IV could be distinguished on Czapek's agar, but less readily on potato dextrose agar. In general, Strains III and IV were most nearly alike. As will be pointed out later, however, the pathogenicity of these two strains differed.

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[9] Dr. Drechsler considered that the only way to deal with these forms was to collect large numbers of strains and then to separate them into their component species, as it is impossible without further study to apply either a new or an old binomial to them.

TABLE XII

Comparison of Growth and Cultural Characters of Four Strains of *Helminthosporium M*

No.	Age of culture, days	Average diameter of colonies cms.			Cultural characters of colonies		
		Oat agar	Czapek's agar	Potato dextrose agar	Oat agar	Czapek's agar	Potato dextrose agar
I	3	3.66	4.73	4.13	Colonies fuscous in center, mostly subepidermal dusky olive green. Trace of white aerial mycelium. Spores few, in center only.	White aerial mycelium in center. Outer zone aniline yellow mostly within substratum. White border. Spores few.	Dense growth of gray to white aerial mycelium in center and covering most of the colony. Orange border. Spores few.
	6	6.00	7.96	6.53			
II	3	4.36	5.23	4.96	Olive green to black colony with light border. Sporulating heavily over whole surface. Aerial growth dark, with radiations.	Olive green to black colony. Aerial mycelium uniform over surface, dark, powdery with spores.	Olive green to black except for a light gray border. Aerial growth dark with radiations. Sporulating heavily over entire surface.
	6	7.23	8.30	7.56			
III	3	4.26	4.86	4.30	Deep slate green. Aerial growth mostly dark, not fluffy. Spores plentiful over whole surface.	Center deep slate green from below, with small circle of white aerial mycelium above. Outer zone light gray turning slate green with age, fluffy. Spores moderately abundant all over colony.	Colonies gray turning deep slate green with age. Aerial mycelium fairly uniform, but becoming densest in center with age. Spores moderately abundant. Slight zonation.
	6	7.30	7.86	6.80			
IV	3	4.36	5.06	4.36	Deep slate green. Aerial mycelium fluffy, abundant, sporulating medium to abundant over whole surface.	Fluffy aerial mycelium over whole surface. Colony fuscous in center bordered with a light gray zone. Spores abundant in center of colony.	Colonies gray turning deep slate green with age. Aerial growth gray becoming more prominent near edge with age. Spores moderately abundant. Slight zonation.
	6	7.33	8.50	6.93			

TABLE XIII

VARIATIONS AND CONSTANTS FOR CONIDIAL MEASUREMENTS OF FOUR STRAINS OF *Helminthosporium M.*

a. Conidial lengths in microns

Strain	Spore classes											Total No.	Constants			
	9	12	15	18	21	24	27	30	33	36	39		Mode	Mean	Standard deviation	Coefficient of variability
I	..	1	..	3	11	24	29	20	10	1	1	100	27	26.01 ± .29	4.28 ± .20	16.08 ± .77
II	..	3	1	7	29	49	11	..	..	..	..	100	24	22.59 ± .21	3.04 ± .14	13.47 ± .64
III	..	..	..	5	11	21	31	21	6	5	..	100	27	26.70 ± .29	4.23 ± .20	15.85 ± .76
IV	1	2	1	3	17	25	28	20	2	..	1	100	27	25.20 ± .31	4.55 ± .22	18.06 ± .86

b. Conidial widths in microns

Strain	Spore classes										Total No.	Constants			
	7	8	9	10	11	12	13	14	15	16		Mode	Mean	Standard deviation	Coefficient of variability
I	..	2	5	14	22	24	21	8	3	1	100	12	11.77 ± .11	1.57 ± .07	13.32 ± .64
II	1	1	3	7	20	30	27	10	..	1	100	12	11.99 ± .10	1.41 ± .07	11.76 ± .56
III	1	2	8	24	29	21	11	4	..	..	100	11	11.05 ± .09	1.38 ± .07	12.49 ± .59
IV	1	8	10	30	29	18	2	2	..	..	100	10	10.50 ± .09	1.33 ± .06	12.66 ± .60

c. Conidial septations

Strain	Spore classes						Total No.	Constants			
	1	2	3	4	5	6		Mode	Mean	Standard deviation	Coefficient of variability
I	1	2	32	62	2	1	100	4	3.65 ± .04	.65 ± .03	17.92 ± .85
II	3	6	91	..	..	..	100	3	2.88 ± .03	.41 ± .02	14.13 ± .67
III	..	1	23	75	1	..	100	4	3.76 ± .03	.47 ± .02	12.54 ± .60
IV	2	2	22	73	1	..	100	4	3.69 ± .04	.63 ± .03	17.01 ± .81

In order to obtain material for comparing the spore dimensions of the four strains, single spore cultures were grown on sterilized mature wheat heads in test tubes under as uniform conditions as possible. The spores were measured in a water mount, with a screw micrometer. Unconscious selection of spores for measurement was avoided by measuring only those which lay parallel to one of the cross hairs of the micrometer, and by measuring all such spores that were encountered in passing from one side of the mount to the other. The length, breadth, and number of septations of each spore were recorded. One of the longest-spored strains was selected for measurement first, in order to determine how many spores it would be necessary to measure in order to avoid errors which might result from measuring an insufficient number. It was found that the differences between the mean lengths of 50, 100, 150, and 200 spores were insignificant. It was decided, therefore, to measure 100 spores of each strain. It was also found that there were no significant differences between the means of different lots of 50 spores and different lots of 100 spores from the same culture. Table XIII summarizes the data from these measurements.

Two of the strains from wheat seed, namely, I and III, have practically the same means for conidial length, but the conidia of Strain II are much shorter, the difference between II and I being 11.23 times the probable error of the difference. Spores of Strain IV are also somewhat shorter than those of Strain I, the difference in this case being 3.32 times its probable error. In mean conidial width, I and II do not differ significantly, while III and IV differ from each other and also from both I and II. The extremes, as represented by I and IV, present a difference which exceeds its probable error 11.12 times. The mean number of septations in I, III, and IV agree closely; their spores are normally 4-septate. Those of II, however, are typically 3-septate. The relative conidial lengths of the four strains are illustrated graphically in Figure 2, page 41. Strain II stands out from the others in having shorter spores with fewer septations.

Strains I and IV were rather virulent on wheat, while Strains II and III were only weakly parasitic (Plate VIII, Fig. 1; also Plate VII, Fig. 1). The effect of the different strains on two varieties of wheat Marquis and Kanred, grown on sterilized soil inoculated with cultures of the organisms, is shown in Table XIV. All strains attacked the roots, invading the cortex as far as the endodermis. (Plate IX, Figs. 3 and 4.) The mycelium was most abundant in the intercellular spaces, altho frequently it was intracellular, some host cells being packed full of the large, dark brown hyphae. Infected portions were often nearly black, owing to the abundance of the dark mycelium in the cortex. Others showed symptoms much like those produced by *H. sativum*. In the case of the more virulent strains (I and IV), roots were frequently attacked throughout their length and were badly stunted, whereas the attack of the other strains was usually more localized. Strains I and IV also produced more pronounced stunting of the tops and frequently dark brown spots on the first seedling leaves, as well as foot-rot similar to that produced by *H. sativum*. The order of virulence of the four strains on the heads and grains was the same as on the seedlings. All strains were re-isolated many times from diseased roots.

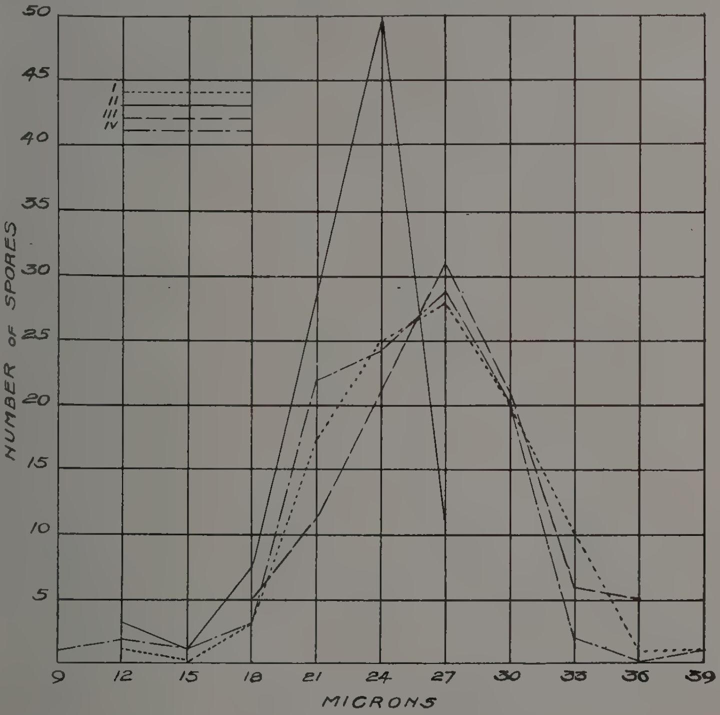

Fig. 2. Relative Conidial Length of Four Strains of Helminthosporium M

TABLE XIV

Comparative Effect of Four Strains of *Helminthosporium M* on Two Varieties of Wheat

Strain	Variety of wheat	Duration of test, days	Stunted seedlings	Seedlings with foot-rot*	Seedlings with root rot*	Mean height, cms.	Total dry weight of tops, gms.	Observations
I	Marquis	38	20/64	$64^{h}/64$	$64^{l}/64$	15.88	1.32	12% dead
I	Kanred	"	60/60	$60^{h}/60$	$28^{l}/60$	8.84	0.92	28% dead
IV	Marquis	"	44/44	$44^{h}/44$	$36^{m}/44$	11.00	0.68	12% dead
IV	Kanred	"	44/68	$68^{h}/68$	$28^{m}/68$	10.50	0.84	16% dead
II	Marquis	"	4/64	$64^{l}/64$	$8^{l}/64$	27.10	3.36	4% dead
II	Kanred	"	32/88	$88^{l}/88$	0/88	21.22	4.64	
III	Marquis	"	20/84	$84^{l}/84$	$12^{tr}/84$	20.74	2.56	
III	Kanred	"	32/76	$72^{l}/76$	$8^{tr}/76$	19.45	2.35	
Control	Marquis	"	11/91	$0^{tr}/91$	0/91	27.81	5.03	

* ^{h}=heavy, ^{m}=moderately heavy, ^{l}=light, ^{tr}=trace.

If there should be in these strains but one collective species or a Linneon, as Stevens (81) and Christensen (13) found with *H. sativum,* it would at least comprise three if not four elementary species. The spores of the four strains have the same general morphology. They are dark olivaceous, usually curved (Plate XI, Fig. 2), each with a small hilum at the lower end, borne in a similar manner (Plate XII, Fig. 5), and germinating usually from both ends (Plate XII, Figs. 1 and 2). Differences in size, however, are found when careful measurements are made and possibly other morphological differences will be found with closer study. It may be that they should be designated as distinct species, but no binomial can be applied until the whole group of small-spored *Helminthosporia* has been studied more carefully.

Inoculation experiments also were made with *H. gramineum* (Rab.) Erik. and *H. teres* Sacc. While the results were somewhat inconclusive, neither appeared to be a virulent parasite of wheat roots.

Helminthosporium sp.—Another very interesting species of *Helminthosporium* was isolated from a diseased wheat root growing in the greenhouse on a continuous-wheat soil obtained from one of the agronomy field plots. This fungus caused dark brown lesions on wheat roots in greenhouse tests and the mycelium penetrated the cortex, but it was only weakly parasitic, if at all. It was readily recovered from the roots. The spores and conidiophores are shown in Plate XI, Figure 4. It is readily seen that the fungus differs from any of the other species of *Helminthosporium* isolated from wheat.[10] It constitutes a well differentiated species which apparently has not been previously described. A new species is therefore proposed with characters as follows:

Helminthosporium pedicellatum n. sp.—Producing, on potato dextrose agar, fine hyaline aerial mycelium with a coarser fuliginous mycelium in the substratum; conidiophores clavate, rarely branched, relatively straight to the point of attachment of the first spore, above which successive spores are produced at the apices of geniculations; measuring 2.5 to 9.5 μ in diameter, producing the first spore usually 100 to 200 μ from the base and developing from 2 to 9 septations below the first spore; total length very variable; brownish olive and thick-walled above but usually lighter and thinner walled towards the base; points of attachment of spores marked by scars. Conidia broadly fusiform, typically straight, widest near the middle, and decidedly attenuated toward both ends, being rounded off at the apex at approximately one-sixth to one-third the maximum width of the spore tho occasionally much broader at the apex, narrowed to a pedicel-like elongation at the base, slightly constricted at the hilum; brownish olive episporium with small pale area adjacent to the hilum, hyaline gelatinous endosporium; germinating from both ends but usually from the base, 1-9 septate but usually 7 septate; measuring 23.42±0.17 by 65.30±0.96 (14.71 to 29.44 by 31.00 to 91.44); measurements based on 100 spores grown on a sterilized mature wheat head.

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[10] A culture was submitted to Dr. Charles Drechsler who considered it a well characterized species, different from any that he had previously seen.

Isolated from wheat roots at St. Paul, Minn., Sept. 28, 1922.

MISCELLANEOUS FUNGI

Other genera contain species which can attack wheat roots but not to such an extent as to interfere markedly with the development of the plants. While they are interesting, it is not considered that they would be very destructive under field conditions. Only a few of them therefore will be mentioned.

Alternaria.—Many strains of this genus were tested but the results were conflicting. In the first series of tests made in test tubes, 47 strains were used, and a few apparently were parasitic. Inoculations were made with the apparently parasitic forms, but the results were variable. All the strains tested in the greenhouse were only weakly parasitic. Diseased portions of the roots were usually localized and brown to black in color, and in these regions the mycelium was found in the cortex only. The fungus was re-isolated frequently.

Stemphylium parasiticum (Thüm.) Elliot.—This fungus, altho able to produce black-point on the seeds, failed to attack the roots to any appreciable extent. Occasionally tiny black lesions were formed on the roots, but usually inoculated roots remained perfectly white and uninjured. The morphology of the fungus corresponds rather closely with that of the species appearing in literature as *Macrosporium parasiticum* Thüm (23). Following Elliot (22), however, this becomes *Stemphylium parasiticum* (Thüm.) Elliot. According to Miyabe (51), *M. parasiticum* and *M. sarcinula* Berk. are identical and *Pleospora herbarum* (Pers.) Rab. is the perfect stage. However, the latter stage has not yet been observed in the writer's cultures.[11] *M. commune* Rab. has also been considered identical with *M. sarcinula* (44) and *M. parasiticum* (80), but Lindau (44) preferred to keep the three species separated until further work confirmed their identity.

Altho the spores (Plate XII, Figs. 6 and 7) of the culture on wheat are similar in shape to those of *M. sarcinaeforme* Cav. on clover (42), they differ in size and also in having a rough exospore. *Stemphylium tritici* Pat. (58) has been reported by Johnson (37) as the cause of floret sterility of wheat, but this undoubtedly is a different species, as the spores are catenulate.

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[11] For this reason it has been deemed advisable not to use the name *Pleospora herbarum* (Pers.) Rab. until the perfect stage of the writer's material has been found and proved to belong to this species. Altho *M. sarcinula* Berk. was described before *M. parasiticum* Thüm., the latter specific name is used because authentic exsiccati material of Berkeley's fungus was not available and the writer's fungus corresponded closely with von Thümen's specimen of *M. parasiticum* (667 de Thümen Mycotheca Universalis).

Phoma sp.—An interesting species of *Phoma* was obtained several times from a continuous-wheat soil, at University Farm, St. Paul. After a week or more in culture, this fungus developed abundant pycnidia and numerous dark brown chlamydospores in the mycelium. Thinking that the latter might belong to another fungus, cultures were several times secured from single pycnospores, but invariably these cultures developed typical chlamydospores. This fungus in inoculated soil readily penetrated the root cortex as far as the endodermis, and frequently the cortex was literally riddled with its mycelium (Plate IX, Figs. 1 and 2). The presence of the fungus was very evident from the fact that the mycelium produced many large chlamydospores. These were observed in root hairs and in epidermal and cortical cells, but never in cells of the central cylinder. The attacked parts were sometimes several centimeters in length, and almost black, but rarely extended to the ends of the roots, being mostly within an inch or two of the seed. Many re-isolations were made from affected roots.

Rhizoctonia.—Stakman (76) inoculated durum wheat seedlings with this fungus. It caused a general blighting of the seedlings but attacked the roots only slightly. The writer did not isolate this fungus in the field. However, in two instances, tiny black sclerotium-like bodies developed on the roots of check plants growing in nutrient agar. *Rhizoctonia* was isolated from these. The fungus could have come from no other source than from the seed, in these instances. Several seedlings were inoculated in test tubes with the fungus, and the sclerotium-like bodies developed on the roots of the inoculated plants, whereas roots of the controls remains normal. The seedlings were also attacked at the foot and some were severely blighted. Greenhouse tests were inconclusive. No sclerotium-like bodies developed on the roots, and the plants grew quite normally.

Repeated unsuccessful attempts were made to isolate the fungus from what appeared to be *Rhizoctonia* mycelium, in tiny spots about 1 mm. long, occurring very abundantly on wheat roots in unsterilized soil, both in the field (Plate II, Fig. 2) and in the greenhouse. The mycelium was usually confined to a few epidermal cells, and often formed a small sclerotium-like body on the exterior. Sometimes the whole root was encircled by the mycelium, which is large, dark brown, and somewhat resembles that of *Rhizotonia.* No rotting was evident and the fungus appeared to cause very slight injury, if any.

Colletotrichum graminicolum (Ces.) Wilson. — In this species Wilson (7) includes several forms that were previously described as distinct species, e.g., *Colletotrichum cereale* Manns. This fungus was only weakly parasitic on wheat roots in the greenhouse and was not studied further.

Aspergillus niger Van Tiegh.—A strain of this fungus, from wheat seed from South Dakota, was pathogenic in preliminary tests and moderately so in the greenhouse. The tips of the roots were rotted most noticeably and the fungus was recovered from the diseased parts. Other trains were non-parasitic.

Acrostalagmus sp.—Several similar cultures of a fungus answering the general description of *Acrostalagmus* (43) were isolated from wheat roots and from the soil. The spores were borne in slimy heads, altho sometimes they were in ear-like masses on verticillate conidiophores. In the young cultures, however, the spores were typically in slimy heads. While this fungus was not particularly destructive, it did cause a characteristic deformity of the roots of some of the wheat seedlings grown in inoculated soil (Plate VIII, Fig. 2). Such roots were stunted, swollen, gnarled, and rotted particularly at the tips. The tops of these diseased plants were invariably badly stunted. However, most of the plants in pots of inoculated soil developed normal or nearly normal root systems. The fungus was readily recovered in pure culture from the diseased roots, but there is little reason to think that it would be destructive under field conditions.

Trichoderma spp.—Several strains of *Trichoderma* which were not identified specifically were slightly parasitic in the greenhouse, but did not appear sufficiently destructive to merit special study. One of these resembled *Trichoderma lignorum* (Tode) Harz., as described by Cook and Taubenhaus (15), altho it may not be identical with it. The others were more similar to *T. koningi* Oudemans which Stakman (76) found to be parasitic on cereal roots.

Other fungi.—Several cultures of a Cephalosporium, resembling *Cephalosporium acremonium* Cda., as well as a few forms which failed to produce conidia, were either non-parasitic or very weak pathogenes in the greenhouse. In addition, many non-pathogenic species were discarded in the preliminary tests. (See Table VI.)

COMPARISON OF THE VIRULENCE OF DIFFERENT FUNGI ON WHEAT

Several fungi were selected which had shown varying degrees of virulence in previous trials. Each was grown on an equal amount of sterilized wheat seed medium, and all cultures were started at the same time. After the medium of the different cultures was thoroly permeated with mycelium, each culture was used to inoculate a pot of sterilized soil in the greenhouse. Twenty seeds of winter wheat (Minhardi, Minn. 1505) were sown in each pot. The results of this experiment are given in Table XV. (See also Plate V, Fig. 4.)

TABLE XV

COMPARATIVE EFFECT OF SOIL INOCULATION WITH DIFFERENT FUNGI ON WINTER WHEAT (MINHARDI, MINN. 1505) IN THE GREENHOUSE

Inoculum	Duration of test, days	Stunted seedlings*	Seedlings with root-rot†	Seedlings with foot-rot	Mean height, cms.	Total dry weight of tops, gms.
None (control)	34	2/20	0/20	0/20	26.54	0.51
“ “	“	0/17	0/17	0/17	30.03	0.48
“ “	“	0/15	1/15	1/15	28.55	0.31
“ “	“	1/18	1/18	0/18	27.10	0.43
Stemphylium parasiticum	“	0/19	0/19	7/19	30.00	0.54
Helminthosporium pedicellatum n. sp.	“	2/18	$18^{l}/18$	2/18	24.19	0.39
Helminthosporium sativum	“	3/12	$12^{h}/12$	2/12	23.60	0.21
Helminthosporium M. Strain I	“	1/13	$13^{h}/13$	0/13	19.73	0.19
Fusarium moniliforme (from seed)	“	10/12	$12^{h}/12$	0/12	12.86	0.13
Fusarium moniliforme (from soil)	“	12/14	$14^{h}/14$	3/14	11.88	0.13
Gibberella saubinetii (soil)	“	3/6	$6^{h}/6$	3/6	13.26	0.07
Fusarium sp. (soil) (Elegans section)	“		No plants emerged from the soil			
Gibberella saubinetii (seed)	“		“ “ “ “ “ “			
Fusarium sp. (foot) (Elegans section)	“		“ “ “ “ “ “			

* The denominator indicates the number of seeds (out of 20) which produced plants. The numerator represents the number of surviving seedlings which were stunted or attacked by root- or foot-rot.

† ^{l}=light. ^{h}=heavy.

In the field, duplicate rod rows were also inoculated in a similar way with cultures of several of the fungi, and sown with both winter and spring wheat. The winter wheat (Minhardi, Minn. 1505) was sown on September 30, 1922, and the spring wheat (Marquis) on May 15, 1923. Notes were taken on the seedlings in each case about six weeks after planting. The percentage seedling survival was taken as an index of the relative virulence of the fungi. The results of these tests are shown in Table XVI.

In the greenhouse the *Fusarium spp.* were more virulent than the *Helminthosporium spp. Stemphylium parasiticum* and *Helminthosporium pedicellatum,* on the other hand, caused little if any injury to the seedlings. After considering the field results also, it is quite evident that *Gibberella saubinetii* is the most virulent parasite tested. This was true not only in the fall when soil temperatures were low but also in the spring when they were relatively high. *Helminthosporium sativum* was also decidedly destructive in the fall, but unfortunately was not included in the tests made in the spring. *Helminthosporium M.* Strain I, while equally as destructive as *Helminthosporium sativum* in the greenhouse, was less so in the field. *Fusarium moniliforme* apparently destroyed nearly as high a percentage of seedlings under high soil temperature conditions (spring) as *Gibberella saubinetii,* but was much less virulent in the fall and somewhat less so in the greenhouse. The two *Fusarium spp.* of the Elegans section were much less destructive in the field than in the greenhouse. The number of seedlings killed, of course, represents only a part of the injury. Naturally most of those that grew were weakened in varying degrees. In further tests it obviously would be desirable to have at least one series on sterilized soil.

TABLE XVI

Seedling Survival of Winter and Spring Wheat Sown in Rod Rows After Inoculating the Soil with Different Fungi

Inoculum*	Percentage of seedlings which survived					
	Winter wheat Minhardi, Minn. 1505)			Spring wheat (Marquis)		
	First series	Second series	Average	First series	Second series	Average
None (Control)	88.5	84.5	86.5	58.0	65.0	61.5
Helminthosporium sativum	35.0	32.0	33.5	...	...	...
Helminthosporium M Strain I	62.5	57.0	59.7	64.0	56.0	60.0
Fusarium moniliforme Strain I	69.5	73.5	71.5	...	...	...
Fusarium moniliforme Strain II	68.5	72.5	70.5	38.0	41.5	39.7
Fusarium sp. Elegans section (soil)	59.5	66.5	63.0	52.5	63.0	57.7
Fusarium sp. Elegans section (foot)	75.5	68.0	71.7	55.5	52.5	54.0
Gibberella saubinetii (roots)	21.5	20.5	21.0	...	...	...
Gibberella saubinetii (seed)	10.5	16.0	13.2	40.5	35.5	38.0

* A fairly high percentage of seedlings was killed in rows to which sterile uninoculated medium was added. This was apparently due to the fact that the soil used was not sterilized and hence the medium introduced formed a suitable substratum for the multiplication of pathogenes present in the soil. On sterilized soil in the greenhouse, on the other hand, there was usually only slight root injury to the control plants and little difference in this respect between controls sown in soil to which the sterile medium was added and those sown in soil to which none was added (see Table X and Plate V).

ANATOMY OF WHEAT ROOTS IN RELATION TO ROOT-ROT

In describing the anatomy of the seminal roots of wheat, Percival (60) distinguishes three principal regions, which are shown in cross-section: (a) a piliferous layer developing root hairs from many of its cells, (b) a broad cortical region, and (c) a central vascular cylinder or stele. The cortical region consists of several layers of thin-walled, parenchymatous cells with small intercellular spaces, and an inner layer or endodermis made up of closely packed cells whose outer walls are thin but whose inner walls become thickened and strongly cuticularized, particularly when old, and whose radical walls also become thickened especially toward the interior of the roots. The third region, the stele, has an outer layer, the pericycle, which consists of a single row of somewhat elongated, thick-walled, lignified cells, uniform in size except for smaller cells opposite the protoxylem elements. Within are seven or eight xylem strands, and alternating with them are the phloem bundles. A large pitted vessel is found in the center of the stele; sometimes there are two or more. The conjunctive parenchyma of the stele also has rather thick walls.

One of the striking features noticed in the examination of sections of diseased roots is the localization of the mycelium of different fungi to particular regions of the root. The piliferous and cortical regions are most commonly attacked, hence we get roots with "loose cortex." In Plate IX, Figures 1 and 2, two sections of a seminal root attacked by *Phoma sp.* are shown. It will be noted that the stele is intact and free from mycelium, while the cortex is riddled with it. A similar condition is illustrated in Figures 3 and 4 of the same plate, which represent sections of roots attacked by *Helminthosporium M.* In both instances the mycelium has penetrated to, but not beyond, the endodermis. In Figures 3 and 4, one or two of the endodermal cells have been entered by the mycelium of *Helminthosporium M,* but no hyphae have penetrated the thick, lignified, inner endodermal walls. On the other hand, in Plate IX, Figure 5, a cross-section of a root is shown in which the central cylinder is primarily attacked. This root was infected with *Fusarium moniliforme.* Figure 6 illustrates a later stage, after the stele has disintegrated. By this time the cortex is also thoroly permeated with mycelium.

From the standpoint of injury to the roots, the latter type of attack is undoubtedly the more serious. It is true that the former may involve the whole root, or the actively absorbing part, and thus reduce its activities materially, but very often only a portion of the root is involved. Such a root may be completely girdled and appear to be cut off, and yet the central cylinder may be intact and the vascular elements may be functional. Lateral rootlets may even be sent out from the stele, through such diseased cortices, showing that it is alive and functioning.

Very evidently the closely-packed cells of the endodermis and their thickened inner walls form a natural barrier against the invasion of many fungi into the central cylinder. The structure and arrangement of the cells of the pericycle as well as those of the conjunctive parenchyma present further barriers to the progress of the mycelium of certain fungi. Percival (60) points out that in roots with decayed cortex, the endodermis, pericycle, and conjunctive parenchyma of the stele become very strongly sclerotic, while cells of the bast and xylem vessels preserve their normal character. Hence these roots would be all the more effectively protected against such decorticating fungi as *Phoma sp., Helminthosporium spp., Alternaria spp.,* etc. This is probably one reason why these fungi cause less pronounced stunting of wheat seedlings than certain species of *Fusarium,* which are able to attack the central cylinder of the roots.

PHYSIOLOGICAL STUDIES OF ROOT-ROTTING ORGANISMS

EFFECT OF TEMPERATURE ON GROWTH

It is particularly important to know the reaction of root-rotting fungi to temperature. Soil temperatures may determine whether or not certain fungi will be able to develop in the soil and attack the roots. Dickson (17), for instance, using *Gibberella saubinetii*, obtained severe blighting of wheat seedlings at soil temperatures of from 16-28° C., whereas no blighting occurred at soil temperatures below 12° C., very little at 32° C., and none at all at 36° C. He further states (18) that since the attack of the organism is chiefly on the young seedling, the range of temperature during the "nursing period" is undoubtedly the important factor in determining the severity of this stage of the disease.

As a preliminary step to soil temperature studies, it was considered advisable to determine first the effect of temperature on the growth of certain root-rotting organisms on culture media. Three fungi were chosen for study, namely, *Fusarium moniliforme* (Strain II); *Fusarium sp.*, Elegans section (soil); and *Helminthosporium M* (Strain I). Petri dishes (10 cm. in diameter) were each poured with 25 cc. of potato dextrose agar, and were inoculated at the center with bits of mycelium from single spore cultures of the different fungi. Duplicate plates of each fungus were then placed at several temperatures between 0 and 39° C. The relative growths at the different temperatures were measured by taking the mean diameters of the colonies on two different dates. The results of these experiments are presented in Tables XVII and XVIII, and also in Plate VII, Figure 2.

TABLE XVII

EFFECT OF TEMPERATURE ON GROWTH OF TWO SPECIES OF FUSARIUM ON POTATO DEXTROSE AGAR

Temperature range, degrees C.	Mean temperature, degrees C.	Diameter of colonies, mm.			
		Fusarium moniliforme Strain II		*Fusarium sp.* Elegans section (Soil)	
		2 days	5 days	2 days	5 days
0.0 - 5.0	4.1	0	0	0.0	0.0
6.5–12.0	8.7	4	5	3.0	4.0
12.5–14.0	12.9	10	21	14.0	24.0
18.0–20.0	19.0	26	42	25.0	42.5
21.5–23.0	22.3	34	59	34.0	58.5
26.5–27.0	26.6	43	74	38.5	66.5
29.0–30.0	29.6	49	78	37.0	64.0
32.0–33.0	32.2	37	58	7.5	28.0
35.0–35.5	35.3	11	14	3.0	3.0
35.5–37.0	36.5	2	4	0.0	0.0
37.0–39.0	38.0	0	0	0.0	0.0

TABLE XVIII

Effect of Temperature on Growth of *Helminthosporium M* (Strain I) on Potato Dextrose Agar

Temperature range, degrees C.	Mean temperature, degrees C.	Diameter of colonies, mm.	
		4 days	6 days
0.0– 5.0	3.5	0.0	0.0
6.5– 8.0	7.6	3.0	6.0
13.0–15.0	13.9	15.0	22.0
18.0–22.0	19.6	26.0	41.5
21.5–24.5	22.8	31.5	50.2
26.0–28.0	27.0	37.5	57.7
29.0–31.5	29.8	39.0	63.0
31.5–33.5	32.0	41.5	53.0
35.0–35.5	35.3	7.0	11.5
36.0–37.0	36.9	7.0	7.5
37.0–39.0	38.0	0.0	0.0

The cardinal temperatures for growth of these three species of root-rotting fungi on potato dextrose agar are therefore approximately as follows:

	Minimum, degrees C.	Optimum, degrees C.	Maximum, degrees C.
Fusarium moniliforme (Strain II)	6.5–12	29.0–30.0	35.5–37.0
Fusarium sp. Elegans section (Soil) ...	6.5–12	26.5–27.0	35.0–35.5
Helminthosporium M. (Strain I)	6.5– 8	29.0–31.5	36.0–37.0

All three species grow best at rather high temperatures. A distinct difference in growth reaction to temperature is shown by the two species of *Fusarium*. *F. moniliforme* will grow at considerably higher temperatures than *Fusarium sp.* (Compare especially their relative growth at 32.2°—Plate VII, Fig. 2.) Strain I of *F. moniliforme* was compared with Strain II at a series of temperatures corresponding to the above, but no differences could be detected between the behavior of the two strains at the different temperatures.

SOIL TEMPERATURE EXPERIMENTS

Four temperature tanks in the greenhouse kept at 15, 20, 25, and 30° C., respectively, were used for these studies. Some fluctuation in temperature occurred, particularly in the 30° tank, but except for short periods the temperatures remained within a degree on either side of the readings indicated for the different tanks.

The soil used was a garden loam which was mixed with sand in the proportion of two parts of soil to one of sand. This soil was steam sterilized and mixed with water, so that it contained approximately thirteen per cent of water by weight. New galvanized iron cans, made especially for the temperature tanks, were then filled with soil. Four cans for each tank were used. The soil in three of these was inoculated, each with a different organism, while the fourth served as a check. The same organisms were used as in the previous temperature relation studies. The inoculum was mixed in the layer of soil in which the seed was planted. Fifty seeds of Marquis wheat per can were planted, and then the weight of each can was recorded. The soil in the various cans was kept at a constant moisture content by weighing the cans frequently and keeping the weights constant by adding water. Weighings were made every three days and in the intervals graduated quantities of water were added according to the amount of evaporation from the soils in the different tanks. Notes were taken at the end of a month. The results are summarized in Table XIX.

TABLE XIX

RELATION OF SOIL TEMPERATURE TO SEEDLING INJURY CAUSED BY THREE SPECIES OF ROOT ROTTING FUNGI

	Control		F. Moniliforme II	
Temperatures, degrees C.	Seedling survival, per cent	Total dry weight, gms.	Seedling survival, per cent	Total dry weight, gms.
14–16 (15.7)*	98	3.86	78	1.91
19–21 (20.5)	95	3.80	78	2.25
24–26 (25.3)	96	4.29	80	2.27
29–31 (30.3)	92	3.09	66	1.52

	Fusarium, Elegans section (Soil)		Helminthosporium M. I	
Temperatures, degrees C.	Seedling survival, per cent	Total dry weight, gms.	Seedling survival, per cent	Total dry weight, gms.
14–16 (15.7)*	6	0.07	92	2.98
19–21 (20.5)	4	0.01	80	3.14
24–26 (25.3)	2	0.03	60	2.54
29–31 (30.3)	8	0.31	58	1.79

* Mean temperatures.

Altho these experiments should be repeated several times to be conclusive, it so happened that in this series the greatest injury resulted at the temperatures nearest the optimum for the growth of each fungus, i.e., at 30° for *F. moniliforme* and *Helminthosporium M.* and at 25° for *Fusarium sp.* It may be, however, that the effect of temperature on the host was more important than the effect on the fungi. Dickson (18), for instance, obtained similar results in his work on the seedling blight of wheat caused by *Gibberella saubinetii*, but the reverse with the seedling blight of corn caused by the same organism. His experiments and those of Eckerson and Dickson (21) lead to the conclusion that the plants are blighted most severely at temperatures which serve best to predispose the respective plants to disease, i.e., relatively high temperatures for wheat and low temperatures for corn. Soil moisture (18) also was found important. Low soil moistures predisposed wheat seedlings to blight even at low soil temperatures.

EFFECT OF HYDROGEN-ION CONCENTRATION ON GROWTH

Czapek's solution, in small Erlenmeyer flasks, was adjusted to different hydrogen-ion concentrations by adding varying quantities of N/5 HCl and N/20 NaOH. The titration data and method of procedure of Karrer and Webb (40) were followed. The pH readings were first made roughly by the colorimetric method, as given by Clark (14), then final determinations were made by means of a potentiometer. Duplicate flasks of each pH were inoculated with each of the three fungi used in the temperature relation studies. This was accomplished with the Fusarium cultures by introducing 1/10 cc. of a spore suspension of each in sterile distilled water into the different flasks, while with *Helminthosporium M* a small bit of mycelium was introduced into each flask of the series. After *Helminthosporium M* had grown for eleven days, and the *Fusarium spp.* for twenty days at room temperature, the mycelial mats were turned out on weighed filter papers in Büchner filters. These were then dried in a gas oven and the dry weights of the mycelial mats were determined. Results are given in Table XX.

TABLE XX

EFFECT OF HYDROGEN-ION CONCENTRATION ON GROWTH OF THREE ROOT-ROTTING FUNGI ON CZAPEK'S SOLUTION

Initial pH	Dry weights of mycelial mats, mg.		
	Fusarium moniliforme Strain II	Fusarium sp. Elegans section (Soil)	Helminthosporium M Strain 1
1.9	120	14	25
2.8	53	57	317
4.4	57	79	321
5.5	54	92	327
7.0	108	123	277
8.0	106	140	261
8.5	150	118	247
9.3	54	110	206

In general the two species of *Fusarium* grew best on an alkaline medium. The reason for the comparatively heavy growth of *F. moniliforme* on the most acid medium has not been accounted for. The other fungi made scarcely any growth at this extreme acid concentration. *Helminthosporium M* grew well throughout the range except in the most acid concentration. Best growth, however, was obtained on the acid side of the neutral point.

TOXICITY STUDIES

An attempt was made to determine whether the injurious effects on wheat seedlings of certain pathogenic species of *Fusarium* might not be due in part to toxic substances either excreted by the fungi or resulting from their growth on culture medium used in the production of inoculum for soil inoculation studies.

Brandes (10) made somewhat similar experiments and concluded that the wilting of bananas caused by *Fusarium cubense* E. F. Smith amended E. W. Brandes, was not due to the plugging of the vessels by the mycelium but probably resulted from toxic excretions by the fungus. Bisby (4) tested the ability of the filtrates of cultures of several fungi, including *Fusarium spp., Rhizopus, Rhizoctonia,* and *Penicillium,* to wilt leaves of potato, ragweed, and other plants. Wilting occurred in a few hours in most cases but was more rapid in old solutions.

The writer grew different species of Fusarium on sterilized wheat seed and on Uschinsky's solution. Using the former medium, cultures were grown in 250 cc. Erlenmeyer flasks containing equal quantities of the medium. With the latter medium, cultures were grown on 250 cc. of the solution in one-liter Erlenmeyer flasks. When the cultures were well developed they were placed in clean porcelain dishes and frozen over night. To each of the wheat cultures 100 cc. of distilled water was added before freezing. They were then thawed and strained through cheese-cloth. The liquid was pressed out of the solid matter by hand, after which the extracts were filtered through filter paper. Bean plants were cut off under water and placed immediately in small vials of the different extracts and watched for signs of wilting. Wilting was more pronounced and occurred more rapidly with beans than with wheat seedlings. Hence beans were used in these experiments. It was thought that wilting might result from high osmotic pressures. Osmotic pressures of some of the extracts were therefore determined by the freezing point method, using the Beckman apparatus to determine the freezing points, and the table of Harris and Gortner (29) to calculate the osmotic pressures. The results are summarized in Table XXI.

The results indicate that the different pathogenic species of *Fusarium* produce deleterious substances which are not present in the media alone or in distilled water. A few tests with non-pathogenic species, however, gave similar results. Growth of the fungi on wheat seed medium increased the osmotic pressure of the extracts, but the increased osmotic pressure did not seem to cause the wilting, for Uschinsky's solution culture extracts gave higher osmotic pressures but were much less effective in causing wilting, possibly because the toxins were more dilute.

TABLE XXI

EFFECT OF EXTRACTS OF FROZEN FUSARIUM CULTURES ON EXCISED BEAN PLANTS

Fungus	Medium	O.P. of extract in atmospheres	Age of culture, days	Notes on wilting
Fusarium moniliforme	Wheat seed	2.676	42	2½ hours, moderate wilting
Gibberella saubinetii	"	1.978	42	2½ hours, pronounced wilting
Fusarium sp. (Pathogenic)	"	4.435	42	do
Check (Wheat seed extract)	"	0.109	42	2½ hours, none
Check (Distilled water)	..	....	..	do
Fusarium moniliforme	Wheat seed	....	30	2 hours, moderate wilting. 12 hours, pronounced wilting
Fusarium sp. (Non-pathogenic)	"	....	30	2 hours, moderate wilting. 12 hours, pronounced wilting
Check (Distilled water)	..	....	30	2 hours, none, 12 hours, none
Fusarium moniliforme	Wheat seed	....	37	2 hours, moderate wilting. 24 hours, pronounced wilting
Gibberella saubinetii	"	4.279	37	2 hours, moderate wilting. 24 hours, pronounced wilting
Fusarium sp. (Pathogenic)	"	4.399	37	2 hours, moderate wilting. 24 hours, pronounced wilting
Check (Distilled water)	..	....	..	2 hours, none, 24 hours, none
Fusarium moniliforme	Uschinsky's solution	6.049	28	2 hours, none, 24 hours, moderate wilting
Gibberella saubinetii	"	5.904	28	2 hours, none, 24 hours, moderate wilting
Fusarium sp. (Pathogenic)	"	7.265	28	2 hours, none, 24 hours, moderate wilting
Check (Uschinsky's solution)	"	6.049	..	2 hours, none, 24 hours, none
Check (Distilled water)	..	....	..	2 hours, none, 24 hours, none

SOIL STERILIZATION EXPERIMENTS

If poor growth and reduced yields of wheat on certain soils are due to root-rotting fungi, then thoro sterilization of seed and soil should restore productiveness. Field observations on continuously cropped and rotated wheat plots of the agronomy division,[12] University Farm, St. Paul, were made. Most of the stunted and unthrifty plants on the continuous-wheat plots were affected with root- and foot-rot, while there was a much lower percentage of diseased plants on the rotation plots. This is indicated by Table XXII, in which fifty plants selected at random on July 17, 1922, from a continuous wheat plot, are compared with fifty from a five-year rotation plot. The plants were brought to the laboratory and washed free of soil and then examined. The notes cover only a very small proportion of the root systems, as only the upper 3 to 4 inches was examined.

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[12] The writer is indebted to Professor A. C. Arny for soil samples and permission to use data from these plots.

TABLE XXII

Comparison of Amount of Foot- and Root-Rot on Marquis Wheat Grown Continuously and in Rotation

Cropping system	Foot-rot	Root-rot		Av. No. of stools per plant	Mean height, cms.	Total dry weight, gms.
	Per cent of plants diseased	Per cent of roots diseased	Severity*			
Continuous wheat since 1893	58	50	43	1,1	52	22.5
Five-year rotation (wheat, pasture, clover, oats, corn)	20	22	24	1.8	122	181.0

* Severity was estimated arbitrarily by allowing 100 points for very heavy infection, 75 for heavy, 50 for moderate, 25 for light, 5 for trace, and 0 for normal roots. The estimates for the 50 plants were then totalled, and the percentage which this figure represented of the total possible severity (5000) was calculated.

Plate X, Figure 2 (A and C) shows the comparative growth of wheat on these two plots in the field; and Figure 1, the beneficial effect of steam sterilization on the growth of wheat seedlings on the continuous-wheat plot soil. Steam sterilization not only controlled root-rot but also increased the vigor of the seedlings very markedly. It is realized, however, that soil sterilization with steam produces marked changes in the chemical and biological content of the soil, as pointed out by Johnson (39), Russel (64), and others. How much of the increased vigor of the wheat seedlings is due to root-rot control and how much to other changes resulting from sterilization is difficult to say, but the former undoubtedly is important. In subsequent soil sterilization experiments, formalin was used as a disinfectant instead of steam, as it was considered that it would cause less pronounced changes in the composition of the soil. A 1 to 50 formalin solution as recommended by Johnson (39) was used.

Experiments were undertaken to determine the relative effectiveness of soil sterilization on fertilized and unfertilized soils, some of which had borne wheat continuously for several years, others which had never been cropped to wheat, and others on which wheat had been sown only once in every three or five years. Fertilizers were applied in order to overcome any plant food deficiency in these soils. A liberal quantity of lime was used in order to render the soils somewhat alkaline. The following fertilizer was applied to two of the series, one of which was also sterilized: Ground limestone at the rate of 3 tons per acre; treble superphosphate, 250 pounds per acre; potassium chloride, 250 pounds per acre; nitrate of soda, 125 pounds per acre; and dried blood, 125 pounds per acre. Sterilization was accomplished by standing pots of soil in a 1 to 50 formaldehyde solution in closed chambers over night. Unsterilized series were kept in water for the same length of time. The soils were then allowed to dry until the fumes of formaldehyde disappeared from the sterilized soil. Two-quart earthenware jars were then filled with the different soils and thirty seeds of sterilized Marquis wheat per pot were planted. The seedlings were later thinned to twenty per pot in order to have a uniform number of plants in the different pots. All pots received equal amounts of water and their positions in the greenhouses were changed at intervals in order to give them similar conditions as regards light and other factors. The results of these experiments are summarized in Tables XXIII and XXIV.

Sterilization of the unfertilized soils in the experiment, summarized in Table XXIII, caused an increased growth over the untreated soil in every case, but this was most pronounced in No. 1. Sterilization and fertilization combined gave the maximum growth in No. 2 and No. 3 but the results in No. 1 were inconclusive, as the tops of the plants were partly destroyed by mice during the experiment. The application of fertilizers alone, as judged by the total dry weight of the tops, was somewhat less effective in increasing growth than sterilization in No. 1 and No. 2, but was more effective on the virgin soil.

TABLE XXIII

EFFECT OF FORMALDEHYDE STERILIZATION OF FERTILIZED AND UNFERTILIZED WHEAT SOILS ON THE GROWTH OF MARQUIS WHEAT

		Growth	Soil treatment			
No.*	Soil	Measurements after 32 days	No treatment	Sterilized	Fertilized	Fertilized and sterilized
1	Continuous-wheat soil	Mean height, cms.	39.70	52.30	53.20	53.10†
		Dry weight, gms.	1.82	2.78	2.62	2.30†
2	Five-year rotation soil	Mean height, cms.	49.30	53.30	55.20	55.50
		Dry weight, gms.	2.86	3.07	2.51	3.36
3	Virgin soil	Mean height, cms.	44.30	48.60	50.00	53.90
		Dry weight, gms.	1.94	2.11	2.40	2.71

* 1 In wheat since 1893.
2 Wheat, clover, pasture, oats, corn.
3 From forestry plantation near the continuous-wheat plot.
† Tops attacked by mice.

Another similar experiment was made. In this experiment, however, a three-year rotation soil replaced the virgin soil and careful notes were taken on the relative severity of root- and foot-rots in the different series. The reaction of the soil was also determined at the conclusion of the experiment. The figures, except those for dry weights in Table XXIV, represent average results from four pots for each of the different treatments.

TABLE XXIV

EFFECT OF FORMALDEHYDE STERILIZATION OF FERTILIZED AND UNFERTILIZED WHEAT SOILS ON THE GROWTH OF MARQUIS WHEAT, ON THE DEVELOPMENT OF FOOT- AND ROOT-ROTS, AND ON THE HYDROGEN-ION CONCENTRATION OF THE SOIL

Soil	Soil treatment	Growth measurements		Disease notes				pH of soil
				Foot-rot		Root-rot		
		Mean height, cms.	Total dry weight, gms.	No. of plants	Degree*	No. of plants	Degree*	
Continuous-wheat soil	a. No treatment	17.15	3.17	64	36.2	60	24.5	6.2
	b. Sterilized	22.37	4.14	0	0.0	8	0.5	6.1
	c. Fertilized	20.17	3.32	56	17.2	48	10.5	7.7
	d. Sterilized and fertilized	26.50	4.17	12	3.0	0	0.0	7.3
Three-year rotation soil	a. No treatment	18.92	2.79	44	20.2	36	7.2	6.3
	b. Sterilized	22.77	3.91	4	0.2	12	0.7	6.0
	c. Fertilized	22.87	3.78	52	19.5	36	7.2	7.7
	d. Sterilized and fertilized	25.47	4.08	0	0.0	4	0.2	7.1
Five-year rotation soil	a. No treatment	18.55	2.93	40	13.5	64	16.7	6.0
	b. Sterilized	27.57	4.33	0	0.0	4	0.2	5.9
	c. Fertilized	21.57	3.30	48	17.2	36	4.2	7.3
	d. Sterilized and fertilized	27.90	4.48	12	1.7	40	4.5	6.9

* Estimated as in Table XXII.

In this experiment there was very little difference in growth between seedlings on the different soils in the untreated series. In the field, however, there were marked differences on these three soils (Plate X, Fig. 2). Soil sterilization with formalin not only reduced the amount of root- and foot-rot in all the soils to a negligible amount, but also caused increased growth of the plants in every case and seemed to increase slightly the acidity of the soil. It is possible that in the field the continuous-wheat soil would be benefited much more than the rotation soils by soil sterilization. Soil fertilization with a liberal applicaton of lime changed the soil reactions from acid to alkaline but did not materially reduce the amount of root-rot in this experiment. It did result in increased growth but was not as beneficial as soil sterilization. On soils which had been sterilized and fertilized, the plants grew best, and there was little foot- and root-rot. While it is obviously not possible to sterilize soil in any extensive way in the field, it is possible to practise crop rotation and in this way, perhaps, accomplish the equivalent of a partial sterilization. This, accompanied by the application of suitable fertilizers, particularly phosphorus and lime to soils requiring these chemicals, should materially aid in controlling root-rots.

OVERWINTERING STUDIES

One of the most important points to determine concerning the life history of root-rotting fungi is their method of overwintering. It is generally known that several overwinter in or on the seed, and it is frequently said that some also overwinter in the soil, on old stubble and other debris, but many such statements seem to be based mostly on observational evidence. Thus, with respect to *Fusarium moniliforme,* Sheldon (69) states that it probably overwinters in the soil; Valleau (84) says that "no evidence has yet been obtained as to the ability of *F. moniliforme* to live over winter in the soil"; while Manns and Adams (48) believe that certain corn parasites, including *F. moniliforme,* live over from season to season on cornstalks, roots, and ears lying in the field.

The writer selected cultures for overwintering studies and grew them on sterilized wheat seed in small flasks, as well as on sterilized wheat straw in large test-tubes. On both media the fungi grew well, and most of them sporulated abundantly. Several 4-inch pots of soil were sterilized by steam, and a wheat seed culture of each fungus was added to each pot, about one inch below the surface of the soil. On November 9, 1922, these pots were placed outside and partly sunk in the soil. The straw cultures were placed in the refrigerator on December 2, and on December 10 were taken out and bound separately in small packets, using ordinary window screening as a covering. They were then stuck in the surface of the soil, outside, near the greenhouse. On April 4 and 5, 1923, viability tests were made.

An attempt was made to recover pure cultures of the different fungi from the original, over-wintered material; spore germination tests were made to see if the over-wintered spores were still viable. The procedure was as follows: In making re-isolations from the soil, a bit of the original culture of each fungus was removed from the soil with a sterilized platinum needle and transferred to a tube of sterile distilled water. After being washed in this for a few minutes, it was transferred to the center of a plate of acidified potato dextrose agar. The washings, as a rule, contained an abundance of spores, and these were tested for germination in syracuse dishes. On the other hand, pieces of the original straw cultures were scraped with a sterilized knife and the scrapings placed on the surface of sterile distilled water in syracuse dishes for spore germination studies. Sections of straw from the different cultures were also placed on moist, sterilized filter paper, in sterilized petri dishes. If, after several days, the fungi were sporulating on the filter paper some distance from the straw, the trials were considered positive.

The results are summarized in Table XXV and are rather interesting. Practically pure cultures of the various fungi were recovered in every instance from the media overwintered in the soil. Moreover, typical spores were produced by all the colonies except those of *Gibberella saubinetii* and *Fusarium sp.*, but the colonies of these fungi were readily recognized, so that there was practically no doubt of their identity. The germinating spores of the different species of *Helminthosporium* and those of *Stemphylium* could, of course, not be mistaken, but those of the *Fusarium spp.* were less readily identified. The spores of three of the *Helminthosporia* germinated, but those of *Helminthosporium N* did not. Christensen (13) found that the mycelium of *H. sativum* over-wintered in the open at St. Paul, but none of the spores germinated. In these tests, however, a comparatively high percentage of the spores of *H. sativum* over-wintered. The tests with the straw cultures gave similar results except that the recovery of *G. saubinetii* and *Fusarium sp.* was not conclusive, as they were not readily identified on the filter paper medium. *Helminthosporium N* and *Stemphylium parásiticum* were not included in these tests.

In general, the results indicate that the mycelium of all the fungi tested and the spores of some readily over-winter on debris in the soil or on its surface.

TABLE XXV

SUMMARY OF OVER-WINTERING STUDIES

Fungus	Kept over winter in soil		Kept over winter on straw	
	Re-isolation in culture	Spore germination, per cent	Re-isolation in culture	Spore germination, per cent
Fusarium moniliforme Strain I	+*	(?)ab†	+*	(?)ab†
Fusarium moniliforme Strain II	+		+	
Gibberella saubinetii	+	(?)ab†	?	
Fusarium sp. (Elegans section)	+		?	
Helminthosporium sativum	+	64	+	84
Helminthosporium N	+	0		
Helminthosporium M Strain I	+	96	+	50
Helminthosporium M Strain IV	+		+	
Helminthosporium pedicellatum	+	4	+	16
Stemphylium parasiticum	+	100		

* Typical cultures of the fungus were recovered.

† ab=abundant.

CONCLUSIONS

Altho most of the fungi tested were not virulent root parasites, those that were parasitic were sufficiently destructive and widely distributed that the results lend further support to Bolley's contention that such fungi contribute materially to the deterioration of wheat yields. While we are not justified in saying that root-rotting fungi are the only cause of reduced wheat yields on land more or less constantly cropped to wheat, we can at least say that they constitute an important contributing factor in this reduction.

The old theory of De Candolle that toxic excreta of plant roots are responsible for unproductiveness has little evidence to support it according to Russel (64, 65) and Livingston (46), but more recent evidence on soil toxins has thrown new light on the cause of unproductive soils (5, 33, 83). The presence of available deleterious aluminum and iron salts in certain soils may be important in predisposing wheat plants to root-rot, as has been shown by Hoffer for corn. The precipitation of these injurious salts by the application of phosphates and lime may explain in part the beneficial action (8) of these fertilizers on certain "wheat-sick" soils.

The fact that root-rotting organisms such as *Gibberella saubinetii, Helminthosporium sativum*, and *Fusarium moniliforme*, live over winter in and on the seed and as saprophytes on plant remains in and on the surface of the soil, and that they are intercrop parasites, make the control of root-rots a difficult problem. Dickson (18), Dosdall (19), Hoffer (83), and others have pointed out, however, that maximum damage from these pathogenes results when conditions for host development are unfavorable. Until resistant varieties can be developed, control measures must consist in providing as nearly optimum conditions as possible for host development, combined with such general preventive measures as seed treatment, crop rotation, and field sanitation.

SUMMARY

1. A study was made of the relation of fungi to root-rots of wheat.

2. Cultures of fungi were isolated for pathogenicity studies from many sources, but chiefly from wheat seeds, from "wheat sick" soil, and from the underground parts of the wheat plant.

3. Species of fungi representing between fifteen and twenty genera were isolated from wheat seeds. *Alternaria* was the most common fungus on the seeds. Several pathogenic species of fungi were obtained.

4. The fungi of black-pointed seeds were studied in particular. *Helminthosporium sativum* was the most common cause of black-point. It was proved by inoculation studies, however, that two other members of this genus, designated in the text as *Helminthosporium N* and *Helminthosporium M*, as well as *Stemphylium parasiticum* can also cause black-point.

5. Most of the fungi obtained directly from the soil were non-pathogenic, but a few pathogenes were isolated.

6. Several pathogenes were isolated from the underground parts of the wheat plant, and a few were obtained from other sources.

7. In preliminary pathogenicity studies in the laboratory, 76 out of 301 cultures tested were marked pathogenic, but many of these were duplicates of the same species.

8. Extensive pathogenicity studies in the greenhouse demonstrated that the important pathogenes of wheat roots encountered in these studies belong to the genera *Fusarium* and *Helminthosporium*. Some species of these genera, however, were also non-pathogenic or weak pathogenes. Certain strains of *Alternaria, Phoma, Acrostalagmus*, and *Aspergillus* penetrated the roots or caused deformities of them, but it was not considered that they would be destructive in the field. Species representing twenty-one other genera were non-pathogenic.

9. Among the *Fusaria, F. graminearum (Gibberella saubinetii)* was the most virulent pathogene of any tested. Certain strains of *Fusarium moniliforme* and two species of the Elegans section, tho less destructive, were also decidedly parasitic on wheat roots. The strain of *F. culmorum* used, apparently had lost its virulence. The other *Fusaria* tested, including *F. lini, F. betae*, and numerous unidentified species, were non-pathogenic or only slightly pathogenic.

10. *Fusarium moniliforme* in addition to wheat also attacked barley, rye, oats, and corn. Four strains of the fungus were studied. One of these, Strain IV, was much less destructive to wheat seedlings than the other three. It could also be distinguishd from them by its reaction on different media. The other strains were much alike, altho Strain I differed slightly from Strains II and III.

11. *Helminthosporium sativum* was in general the most common and the most destructive species of *Helminthosporium* found. At least three other species of *Helminthosporium* were isolated from wheat.

12. The species of *Helminthosporium* designated *Helminthosporium N* has conidia which are significantly narrower than those of *H. sativum.* This organism produced symptoms similar to those caused by *H. sativum* on different parts of the wheat plant, including the roots, but it was much less virulent.

13. Several similar small-spored *Helminthosporia* were isolated. Four strains, three from wheat seed and one from a millet leaf, were studied. Two of these were destructive pathogenes, and attacked different parts of the wheat plant besides the roots, while the other two were much weaker pathogenes. The four strains were readily distinguished by cultural characters and differences in pathogenicity. Significant differences in the morphology of their spores were shown by biometrical studies. At least three elementary species, or perhaps true species, were represented.

14. A new species of *Helminthosporium, H. pedicellatum n sp.,* is described. It was isolated from diseased wheat roots and when these were artificially inoculated the cortex was penetrated but the injury was slight.

15. Most fungi attacked the piliferous and cortical regions of the root only. The structure and arrangement of the endodermal cells seemed to constitute an effective barrier against the entrance of these fungi into the stele. However, several species of *Fusarium* attacked the central cylinder primarily, and caused disintegration of the cell walls.

16. The seedling stage of the wheat plant is undoubtedly a critical period in its life from the standpoint of root-rots. The seminal roots seem particularly susceptible to attack while the adventitious roots seem somewhat more resistant.

17. *Fusarium moniliforme* Strain II and *Helminthosporium M,* Strain I, grew best at about 30° C., whereas *Fusarium sp.* (Elegans section) had a slightly lower optimum. Two strains of *F. moniliforme,* one from seed and the other from soil, showed approximately the same reaction to different temperatures.

18. *F. moniliforme* Strain II and *Helminthosporium M* Strain I, and *Fusarium sp.* (Elegans section) in one experiment were more destructive to wheat seedlings at a soil temperature nearest their respective optimum temperatures for vegetative growth, than at other temperatures between 15 and 30° C.

19. On Czapek's solution, *F. moniliforme* Strain II and *Fusarium sp.* (Elegans section) grew best when the medium was somewhat alkaline (pH 7 to 8.5), while *Helminthosporium M* Strain I, grew best on the acid side of the neutral point (pH 2.8 to 5.5).

20. Extracts of frozen cultures of pathogenic and non-pathogenic species of *Fusarium* caused wilting of excised bean plants, whereas no wilting occurred during the experiment in the medium alone (Uschinsky's solution) or in extracts of the medium (wheat seed) or in distilled water. Wilting apparently was not due to high osmotic pressure of the extracts.

21. Formaldehyde disinfection of soils which had been cropped to wheat for different periods of time caused increased growth of wheat seedlings over those on untreated soils in all cases. In one experiment this increase was most pronounced on a continuous wheat soil, as compared with a virgin soil and a five-year rotation soil. Increased growth was accompanied by root-rot control. The application of fertilizers, including the liberal use of lime, also caused marked increase in growth but was less effective than soil sterilization in controlling root-rot. Wheat plants grew best on soil which had been disinfected and fertilized. In farming practice the rotation of unrelated crops probably offers the best substitute for soil sterilization.

22. Cultures of *Fusarium moniliforme, Gibberella saubinetii, Fusarium sp.* (Elegans section), *Helminthosporium sativum, Helminthosporium N, Helminthosporium M, Helminthosporium pedicellatum,* and *Stemphylium parasiticum* were recovered from inoculum of each on wheat seed over-wintered under the soil surface from November 9, 1922, to April 4 and 5, 1923, at St. Paul. The over-wintered spores of *H. sativum, Helminthosporium M, H. pedicellatum,* and *Stemphylium parasiticum* germinated. Several of these fungi also over-wintered on straw kept on the surface of the soil.

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EXPLANATION OF PLATES

Plate I

Effect of Inoculating Marquis Wheat Seedlings with *Fusarium spp.* Illustrating Method Used in Preliminary Pathogenicity Studies

Photograph taken one month after inoculation

1. Inoculated with *Fusarium moniliforme* Strain II from the soil
2. Inoculated with *Fusarium moniliforme* Strain I from wheat seed
3. Inoculated with *Fusarium graminearum* (*Gibberella saubinetii*) from wheat roots
4. Uninoculated—Control
5. Inoculated with *Fusarium graminearum* from wheat seed
6. Inoculated with *Fusarium graminearum* from wheat roots
7. Inoculated with *Fusarium graminearum* from wheat roots

Plate II

Fig. 1. Black-Point of Wheat Caused by Different Fungi

A. Marquis seeds from head inoculated with *Helminthosporium sativum*

B. Left—Marquis seeds from head inoculated with *Helminthosporium M*
Right—Kubanka seeds from head inoculated with *Helminthosporium M*

C. Marquis seeds from head inoculated with *Stemphylium parasiticum*

The two upper rows of kernels are from inoculated heads and show embryo discoloration. The two lower rows are from uninoculated heads and show normal embryos.

Fig. 2. Three minute black sclerotium-like bodies on wheat roots collected in the field at St. Paul

Plate III

Effect on Growth of Marquis Wheat Seedlings of Soil Inoculation with *Fusarium moniliforme*

Fig. 1. Comparison of the relative virulence of Strains IV and III. All pots were planted at the same time, and all inoculated pots received approximately equal quantities of inoculum

A. Soil inoculated with Strain IV

B. Soil uninoculated—no medium added to soil—control

C. Soil inoculated with Strain III

Fig. 2. Typical series used in pathogenicity tests in the greenhouse

A. Soil uninoculated—culture medium added to soil—control

B. Soil inoculated with *F. moniliforme* Strain I

Plate IV

Effect on Roots and Tops of Marquis Wheat Seedlings of Soil Inoculation with Two Strains of *Fusarium moniliforme*

Photograph taken one month after planting

1. Seedlings from soil inoculated with Strain I
2. Seedlings from uninoculated soil (medium added)—control
3. Seedlings from soil inoculated with Strain II

Plate V

Effect on Different Cereals of Soil Inoculation with *Fusarium moniliforme* Strain I

Fig. 1. A. Effect on wheat—left to right—control (no medium added to soil) two pots of inoculated soil, control (medium added to soil)

B. Effect on rye—left to right—as in A

Fig. 2. A. Effect on barley—left to right—as in Fig. 1, A

B. Effect on oats—left to right—as in Fig. 1, A

Fig. 3. A. Effect on field corn—left to right—control (no medium added to soil), control (medium added to soil), two pots of inoculated soil

B. Effect on sweet corn—left to right—two pots of inoculated soil, control (no medium added), control (medium added to soil)

Fig. 4. Comparative virulence of different fungi on Minhardi wheat

The different pots received approximately equal quantities of inoculum and were each sown with twenty seeds of Minhardi wheat. Photograph taken 12 days after planting.

1. Soil inoculated with *Gibberella saubinetii* from wheat seed.
2. Soil inoculated with *Fusarium sp.*, Elegans section, from wheat roots
3. Soil inoculated with *Gibberella saubinetii* from wheat roots
4. Soil inoculated with *Fusarium moniliforme* Strain II from the soil
5. Soil inoculated with *Fusarium moniliforme* Strain I from wheat seed
6. Soil inoculated with *Helminthosporium M* Strain IV from millet leaf
7. Soil inoculated with *Helminthosporium sativum* from wheat seed
8. Soil inoculated with *Helminthosporium pedicellatum* from wheat roots
9. Soil inoculated with *Stemphylium parasiticum* from wheat seed
10. Uninoculated—control

Plate VI

Comparison of Cultural Characters of Strains I, II, III, and IV of *Helminthosporium M* on Three Different Media: Oat Agar (left), Czapek's Agar (eenter), and Potato Dextrose Agar (right)

Plate VII

Fig. 1. Effect of soil inoculation with *Helminthosporium M* Strain I on tops and roots of Marquis wheat seedlings

A. Grown in inoculated soil

B. Grown in uninoculated soil

Fig. 2. Effect of temperature on vegetative growth of two species of *Fusarium* on potato dextrose agar

A. *Fusarium sp.* (Elegans section)

B. *Fusarium moniliforme*

Plate VIII

Fig. 1. Effect of soil inoculation with four strains of *Helminthosporium M*, on Kanred wheat. All pots were planted at the same time and all the inoculated pots received approximately equal quantities of inoculum.

A. Left, soil inoculated with Strain II
Right, soil inoculated with Strain III
B. Soil uninoculated—control
C. Left, soil inoculated with Strain IV
Right, soil inoculated with Strain I

Fig. 2. Effect of soil inoculation with *Acrostalagmus sp.* on Marquis wheat roots. All three seedlings were taken from the same pot. The roots of the two outer seedlings showed marked stunting, hypertrophy, and other deformities. Their roots were also rotted, but chiefly at the tips. The roots of the central seedling, however, were more typical of the majority of the plants in the inoculated pots.

Plate IX

Photomicrographs of Cross-Sections of Seminal Roots of Marquis Wheat Attacked by Different Fungi

Fig. 1. Cross-section of a root, showing the mycelium of *Phoma sp.* confined to the cortex

Fig. 2. Cross-section of another root attacked by *Phoma sp.*, showing the abundant production of chlamydospores by the mycelium in the cortex

Figs. 3 and 4. Sections of two seminal roots, showing the invasion of the mycelium of *Helminthosporium M* as far as the endodermis. A few of the endodermal cells have been entered but the stele has not been attacked.

Fig. 5. Cross-section of a root attacked by *Fusarium moniliforme*. The mycelium of the fungus is very plentiful in the cells of the central cylinder and the walls of these cells have commenced to decay. The cortex is much less severely attacked.

Fig. 6. Cross-section of another root attacked by *Fusarium moniliforme*. The stele has disintegrated and the cavity is filled with mycelium. In this stage of decay the cortex is also thoroly invaded with mycelium but the cells have not entirely broken down.

Plate X

Fig. 1. Effect of steam sterilization of a "wheat sick" soil on the growth of Marquis wheat seedlings

This soil had borne wheat continuously since 1893 except for 1915 and 1916, when it was planted to corn.

A. Seedlings grown on steam sterilized soil
B. Seedlings grown on unsterilized soil
Ten seeds were planted in both A and B.

Fig. 2. Relative growth of Marquis wheat under different systems of rotation

A. Fifty plants selected at random from a five-year rotation plot
B. Fifty plants selected at random from a three-year rotation plot
C. Fifty plants selected at random from a plot which had been in wheat continuously since 1893, except in 1915 and 1916.

Plate XI

Conidia and Conidiophores of Different Species of Helminthosporium Isolated from Wheat

All drawings were made with the aid of a camera lucida, to the scale indicated on the plate.

1. Three conidia of *Helminthosporium sativum*
2. Four conidia of *Helminthosporium M* Strain I
3. Three conidia of *Helminthosporium N* showing one still attached to a conidiophore
4. Conidia, germinating conidia, and conidiophores of *Helminthosporium pedicellatum*

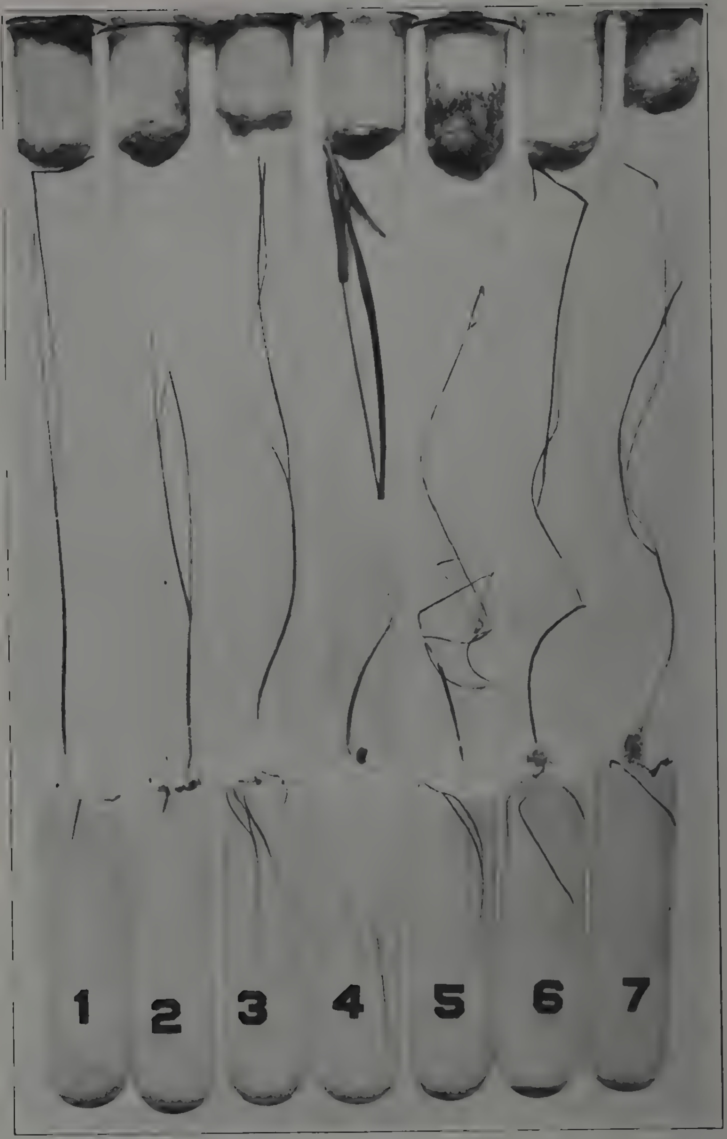
Plate XII

Drawings of *Helminthosporium M*, Strain I and *Stemphylium parasiticum* Illustrating Conidial and Conidiophore Germination

All drawings were made with the aid of a camera lucida, to the scales indicated on the plate.

1. Germinating conidium of *Helminthosporium M*, showing rapidity of germ-tube growth. The figures are in minutes. The first germ-tube was visible in fifty minutes.
2. Two germinating conidia of *Helminthosporium M,* showing typical germination from the end cells of the spores
3. A conidium of *Helminthosporium M,* showing one germ-tube coming from a central cell of the spore
4. Germinating conidiophore of *Helminthosporium M*
5. Conidiophores and attached conidia of *Helminthosporium M*
6. Germinating conidia of *Stemphylium parasiticum* from wheat
7. Conidia and conidiophores of *Stemphylium parasiticum* from wheat
8. Germinating conidiophores of *Stemphylium parasiticum* from wheat

PLATE I



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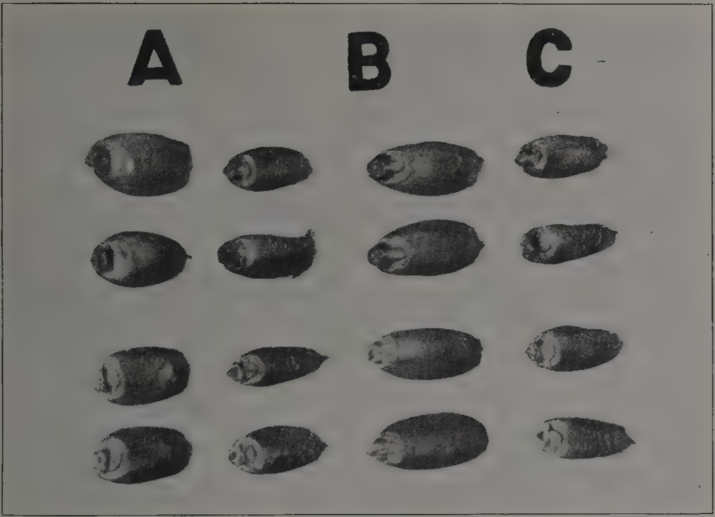

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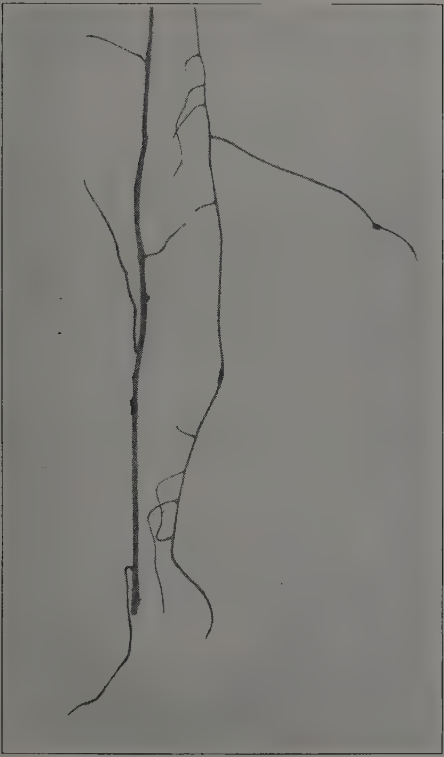

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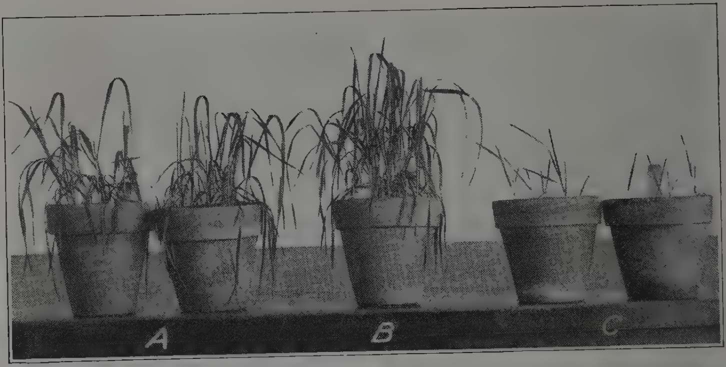

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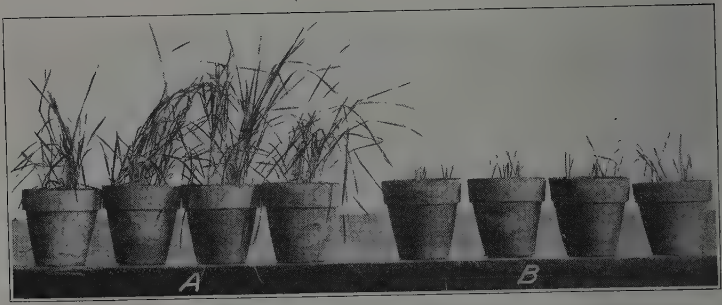

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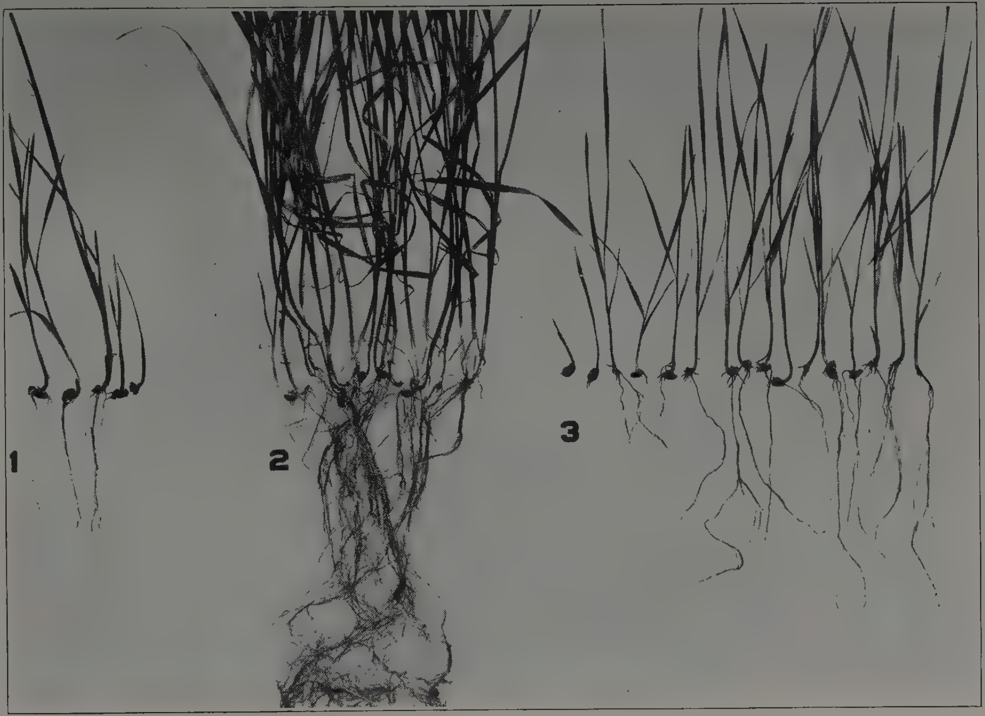

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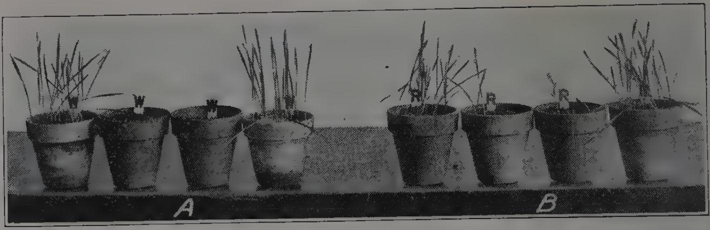

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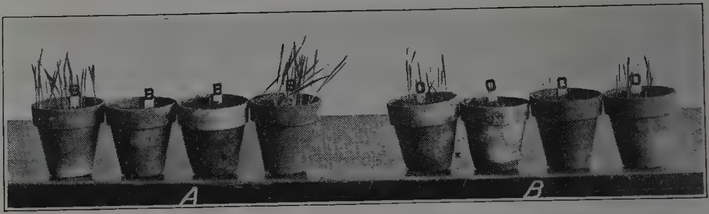

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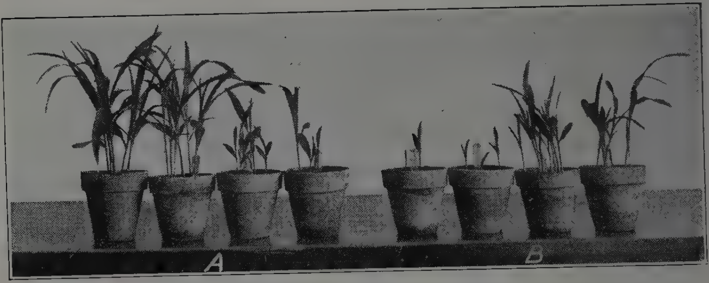

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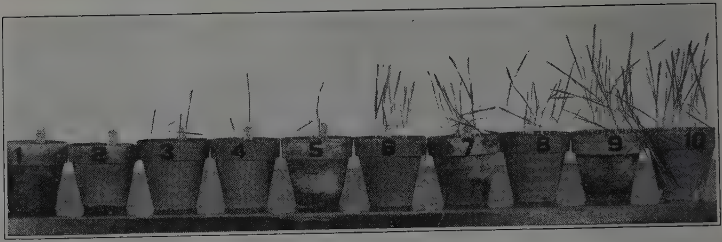
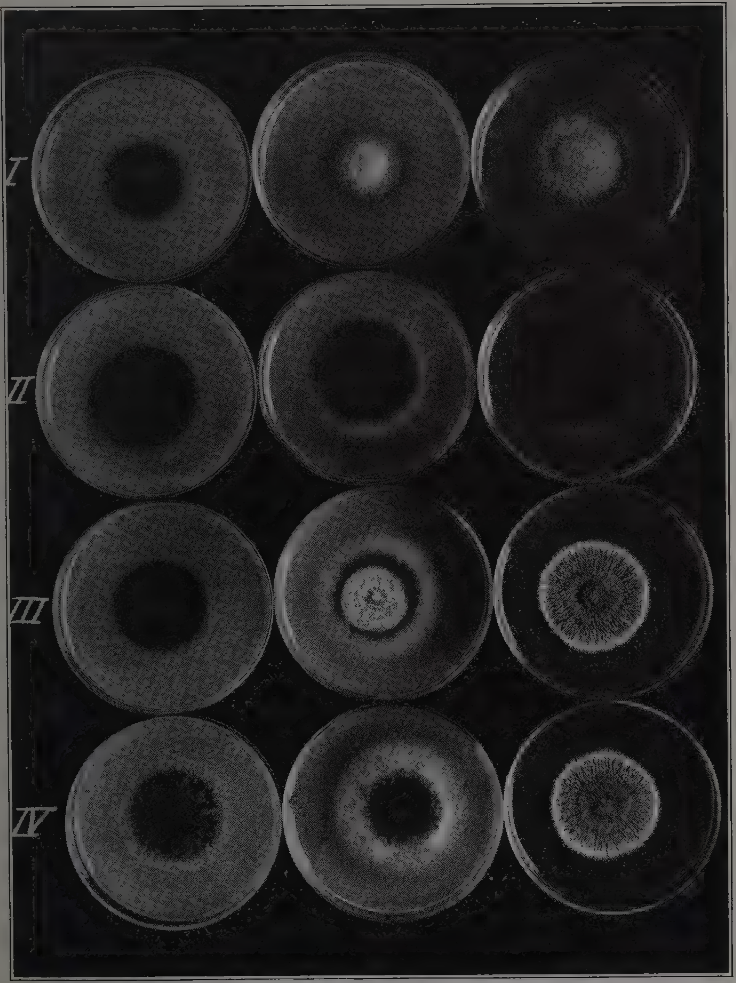


Figure 4

PLATE VI



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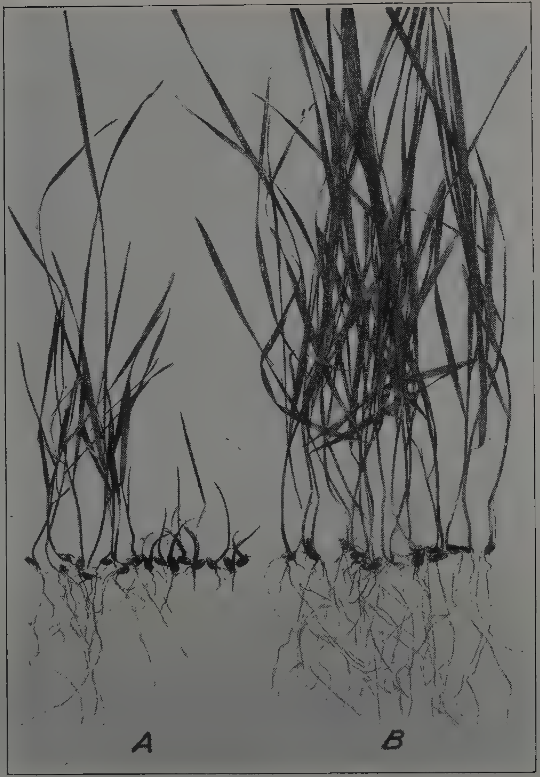

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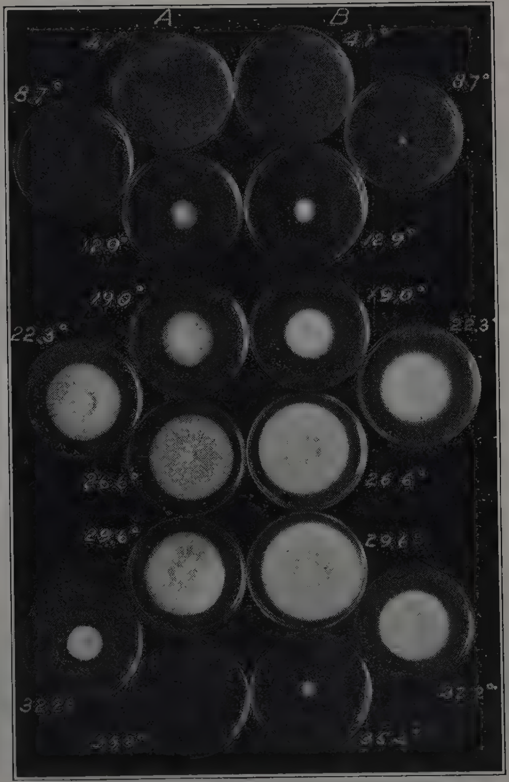

Figure 2

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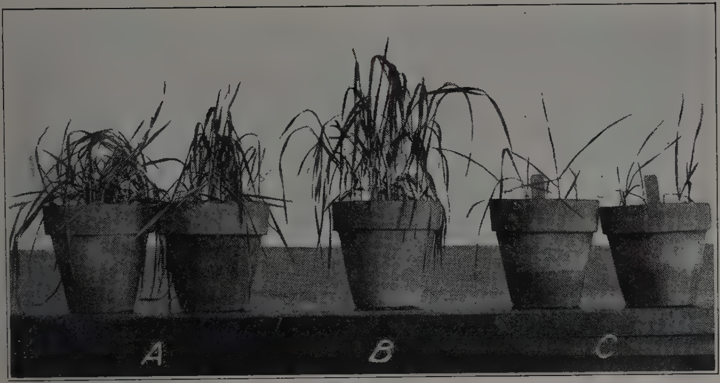

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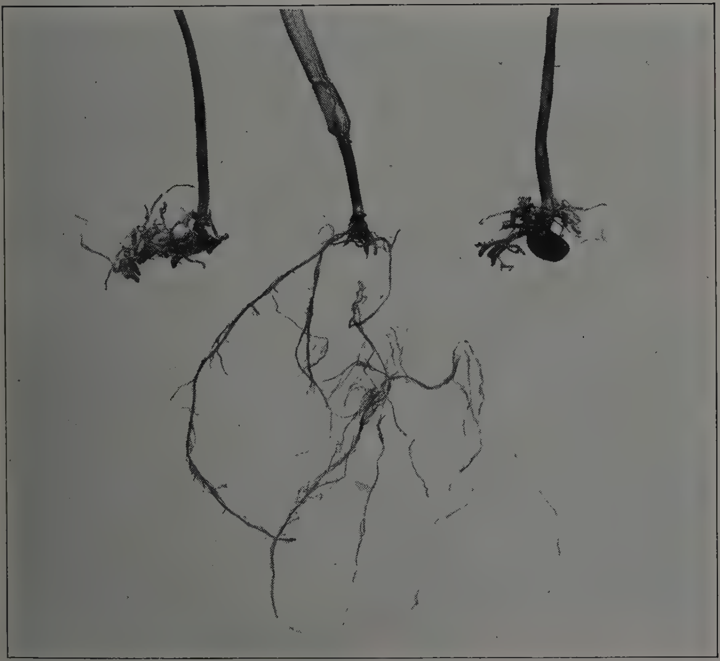
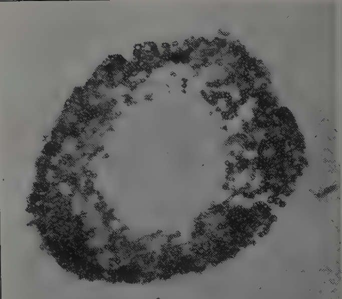


Figure 2

PLATE IX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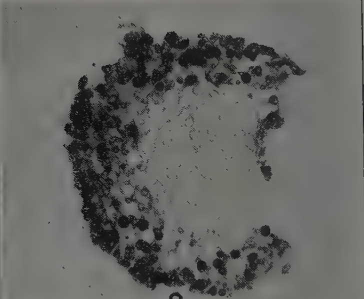
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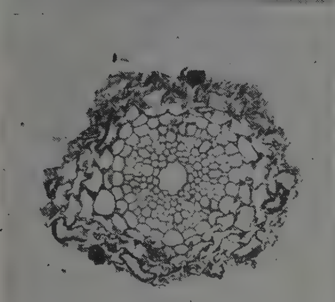
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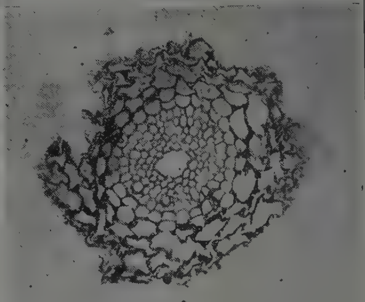
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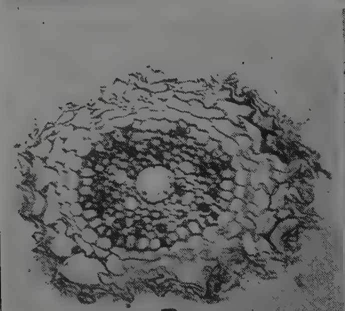
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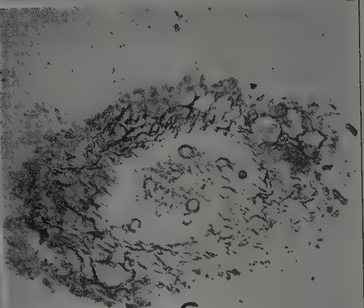
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PLATE X

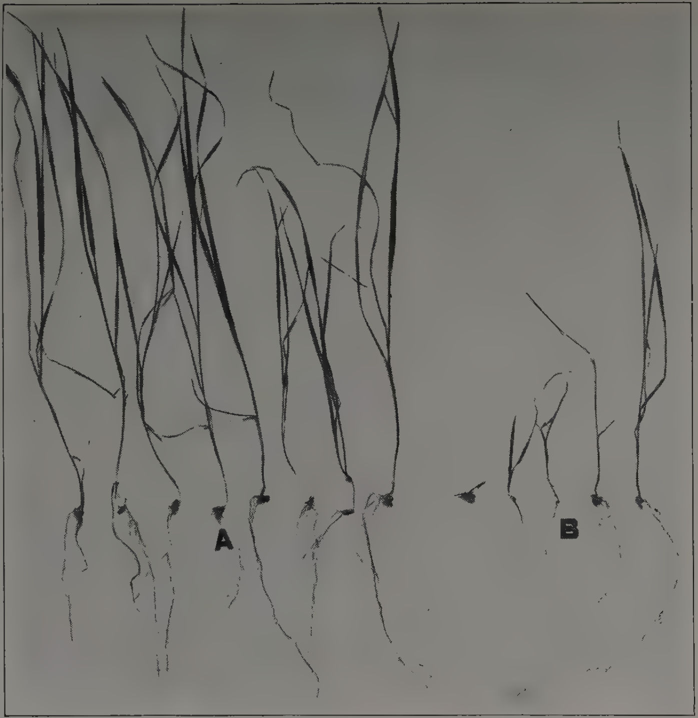

Figure 1

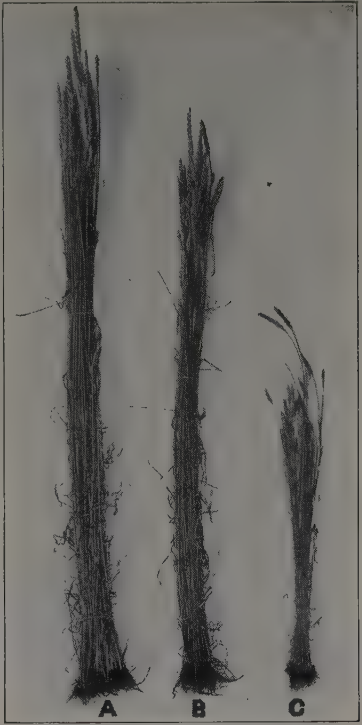

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PLATE XI

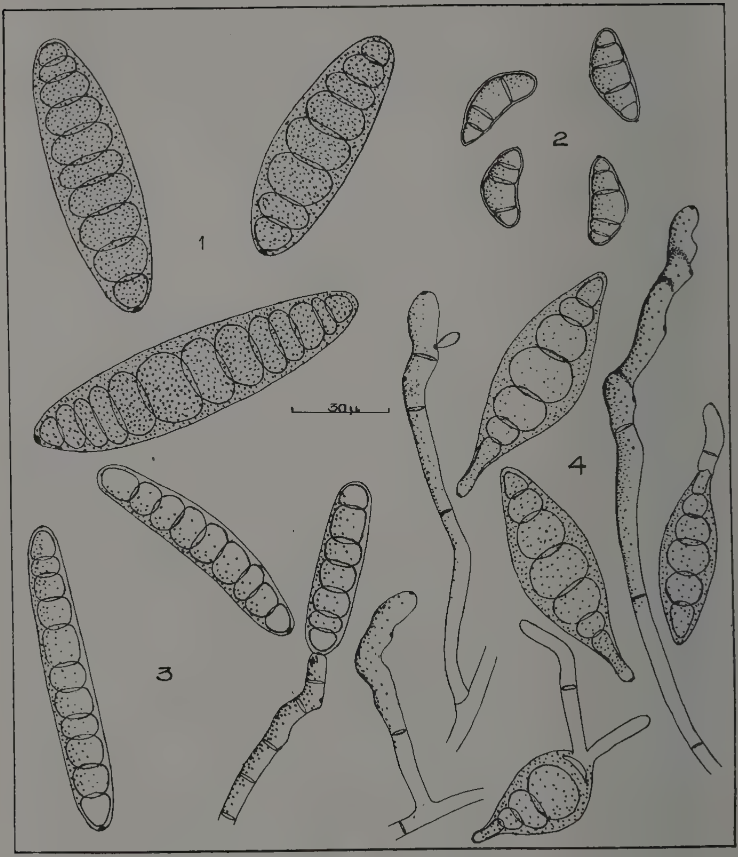
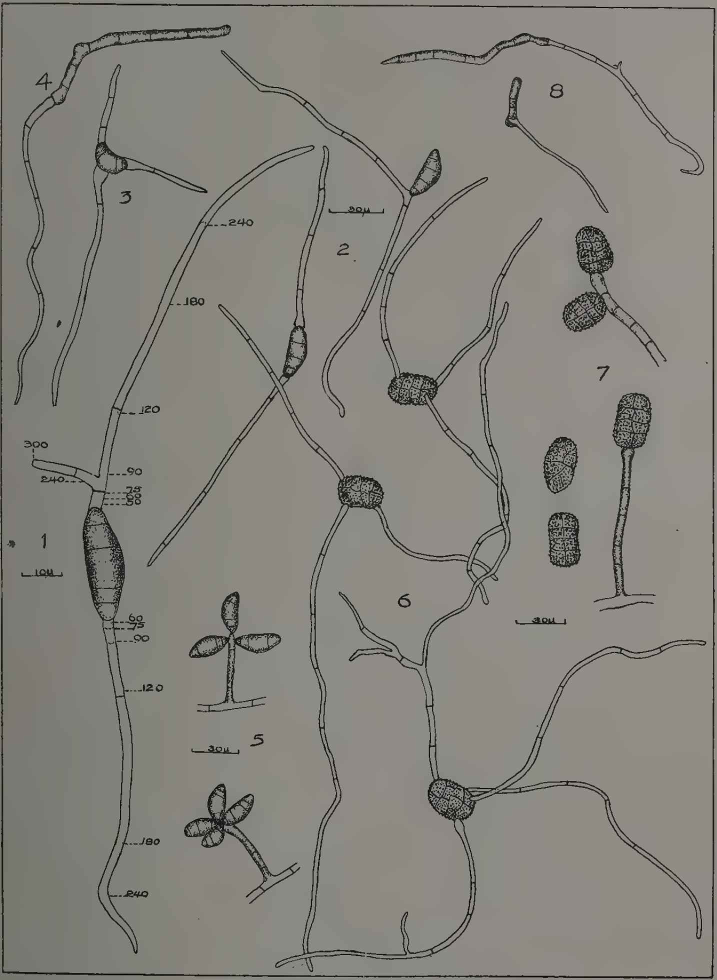


PLATE XII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TECHNICAL BULLETIN 23 MARCH, 1925

The University of Minnesota
Agricultural Experiment Station

A Study of the Physiologic and Pathologic Changes Occurring in the Reproductive Organs of the Cow Following Parturition

W. L. Boyd
Division of Veterinary Medicine

UNIVERSITY FARM, ST. PAUL

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A STUDY OF THE PHYSIOLOGIC AND PATHOLOGIC CHANGES OCCURING IN THE REPRODUCTIVE ORGANS OF THE COW FOLLOWING PARTURITION

By W. L. Boyd

INTRODUCTION

In pursuance of studies on the subject of sterility in cattle, data are being collected on the various changes which occur in the reproductive organs following parturition. Special attention is being given to the different processes involved in involution and subinvolution of the uterus.

The animals from which data were collected were with few exceptions purebred cows owned by the University. This made possible frequent and in many cases daily examinations. Treatment was not applied to cows which calved normally, unless symptoms of infection appeared during the process of involution. Cows affected with metritis, retention of the fetal membranes, trauma, or other diseased conditions frequently occurring incident to parturition, were given medical and surgical aid in order to preserve the reproductive powers. In cases in which the corpus luteum failed to undergo degeneration and thereby prevented renewed ovulation, the corpus luteum was removed in order to maintain at as high a point as possible, the breeding efficiency of the herds. The amount of time required for the completion of involution varies considerably, depending largely upon the condition of the reproductive organs at the time of parturition. Cows which gave birth to strong vigorous calves and promptly expelled the fetal membranes, seldom suffered with infections which would retard involution.

The uterus rapidly diminished in size and in many instances could be described as having returned to its normal non-gravid shape and position within from twelve to fourteen days; in other cows, in which there was mild infection, three weeks was required. Cows that retained the fetal membranes as a result of the Bang organism or other bacteria capable of producing similar lesions, together with secondary invaders, very often required from thirty to sixty days.

CHANGES OCCURRING IN THE VAGINA

The vagina after parturition will often present a bruised edematous, hemorrhagic, and in certain cases of dystokia, lacerated appearance. The vagina as a rule quickly regains its muscular tonicity. The extravasated blood is absorbed in a week or ten days and unless there is extensive laceration with necrosis of the mucous membrane, the wounded areas are soon repaired. If the vagina is severely injured, necrosis usually follows. This often permits the invading bacteria to enter into the fibrous coat and even into the pelvic cavity, producing peri- and para-metritis with or without abscess formation. The vulva frequently contains blood suffusions, is edematous, and occasionally lacerated. This structure regains its normal tone in a few days. Cervicitis is of common occurrence following parturition and frequently inhibits involution, and if tissue damage is extensive the reproductive power of the animal may be destroyed.

HYPERTROPHY OF THE VAGINAL WALLS

This is frequently seen during the late stages of gestation, following parturition, and occasionally in unbred heifers. The wall of the vagina, 10 to 12 cm. anterior to the vulva, laterally and dorsally, becomes hyperplastic so that partial collapse of the vagina results, ordinarily seen only while the animal is recumbent. Severe inflammatory changes in the post-parturient animal sometimes develop and result in more complete prolapse, induced by straining from the irritation. The condition is ordinarily successfully treated through surgical removal of the hyperplastic portion of the wall and the accumulated fat tissue in the pelvic cavity in close proximity to the fibrous coat of the vagina.

Prolapse of the vagina is seen in cases other than from the development of hypertrophic walls. It is occasioned by advanced pregnancy, especially in fleshy animals, and from injuries following parturition. The prolapse is frequently not complete, and is visible only while the animal is lying down, but may be severe and complete.

CHANGES IN THE OS UTERI

The cervical canal closes very rapidly following parturition, the act being especially rapid when the fetal membranes are promptly discharged. Following normal calving, the cervix, within 10 or 12 hours will have contracted to the extent that there will be some difficulty in passing the hand through the canal into the uterine cavity. In cases of retained fetal membranes, contraction of the cervix is less rapid, particularly if some of the membranes are in and protruding beyond the canal. The cervix is frequently more or less lacerated, hyperemic, hemorrhagic, and edematous. The mucous plug of pregnancy which gives way at the beginning of parturition, clings tenaciously to the walls of the canal and small portions of it will often be found attached for twenty-four to thirty-six hours after parturition.

ACTION OF THE UTERUS FOLLOWING PARTURITION

The changes occurring in the uterus after parturition are physiologic, but they are close to the border line of pathology, and if they occurred elsewhere in the animal body they would be considered as pathologic. This explains the frequency and severity of infections if certain bacteria invade the uterine cavity. The rapid diminution of the uterus is brought about by absorption of the tissue juices and certain changes in the muscle fibers. Some authorities believe that the muscle cells undergo fatty changes, while others do not. Compression of the uterine blood vessels by the contraction of the uterus results in anemia, which permits of the changes mentioned. DeLee (3) in describing the changes occurring in the uterus of the human, states that thrombosis occurs in the walls of the deeper veins only in pathologic cases, but a superficial thrombosis is not abnormal. In one of the experimental animals which suffered with severe metroperitonitis, extensive thrombosis of the middle uterine artery was encountered. The affected vessel was without difficulty palpated by way of the rectum. In another animal an aneurism of the middle uterine artery was discovered.

Knowledge of the changes involving the uterine mucous membrane is very meager, but there is no doubt that these changes are less rapid than the changes occurring in the musculature of the organ. It seems quite probable that cows which calve normally in every respect and which receive proper care and feed during their post-parturient stage, seldom complete all the processes involved in involution inside of thirty days.

RELATION OF THE PLACENTA TO INVOLUTION

The placenta of the cow is poly-cotyledonary in type and the arrangement is so complicated that it is not so easily detached or so readily expelled as in animals whose placenta is diffuse. Following the expulsion of the fetus and fetal fluids, the lumen of the uterus materially decreases, the muscles of the uterine walls contract, and the cervix decreases in vascularity and rapidly contracts. The cervical canal is very frequently approximately closed from 12 to 24 hours after parturition. The fetal membranes are as a rule expelled within from 4 to 6 hours. In a small percentage of cases they will be expelled in 2 or 3 hours, and not infrequently they will remain attached for 7 or 8 hours even tho there is no inflammation. When the fetal membranes are retained for more than 10 or 12 hours, it is quite evident that placentitis is present, and they will have to be removed manually or allowed to remain in the uterus to undergo putrefaction, being finally expelled as a putrid mass, consisting mainly of fluid, pieces of the membranes, and tissue debris. The separation of the fetal and maternal placenta is the result of cessation of the fetal circulation which permits the falling away of the chorionic villi from the crypts of the cotyledons. The expulsion of the membranes is effected by their weight and the muscular contractions of the uterus. As stated by De Bruin (1) the numerous placentae of the cow do not separate from the uterus simultaneously, but one after the other. In experimental animals, immediately after calving, there was often much difficulty in obtaining enough placental attachments for bacteriologic and pathologic study, yet the entire fetal membranes of these animals were frequently expelled 4 or 5 hours later. In normal separation of the fetal membranes, severe hemorrhages are only rarely observed in large animals. Retention of the fetal membranes as a result of placentitis seriously interferes with regression of the uterus, through interference with muscular contraction, which brings about uterine inertia. Inertia of the uterus also may be present before or at the time of parturition. Placentitis is a common symptom of bovine infectious abortion and according to the work of Theobald Smith (2) *Bacterium abortus* Bang has a predilection for the chorionic epithelium. On the other hand, several experimental animals suffered with retained afterbirth in which the Bang bacillus could not be isolated from the placenta or from guinea pigs inoculated with suspensions of it. The blood of these cows was also negative to both the agglutination and complement fixation tests. The reduction of the uterus is subject to many variations. Inflammation of the placenta, if at all extensive, means retained fetal membranes. This invites sepsis and results in retarding or stopping involution. Involution, however, acts as a barrier to infection and it is a well established fact that the uterus which has good muscle tone and contracts rapidly, seldom absorbs bacteria or their toxins.

APPEARANCE OF THE LOCHIA

One of the striking events in the puerperium is the appearance of the lochia. Lochia may be defined as the uterine, cervical, and vaginal discharges which follow for several days after the expulsion of the fetus. The lochia consists of a serosanguineous exudate, at first red, but soon becoming brown and then clear owing to the appearance of mucus which may at times contain particles of pus and tissue debris, giving the lochia a cloudy appearance. If not evacuated successfully, the lochia may form a favorable medium for the development of bacteria. Cases are met with in which particles of the placenta have been retained and in which the cervix closes so rapidly that the uterus can not evacuate its contents. The nature and appearance of the discharge is an important guide to the condition and progress of the patient. A thin, watery, reddish brown, malodorous discharge signifies danger and means that the uterus is undergoing inflammation and is not contracting because of lack of muscle tone brought about by the infective agents. This condition permits the absorption of bacterial products which causes elevation of temperature and not infrequently enteritis, which is evidenced by a copious watery diarrhea. Mastitis is also a common complication. In severe cases terminal pneumonia is not uncommon. These conditions are most common in cases in which the fetal membranes have been wholly or partially retained, but may occur in cows in which the membranes are entirely expelled. Cows that experience normal parturition will in almost every instance have an abundance of clear mucus resembling the mucous discharge of estrum in the vagina and cervical canal. This phenomenon appears early preceding the serosanguineous discharge of lochia.

PYOMETRA

Involution is frequently retarded or stopped by a suppurative inflammation of the uterus called pyometra. Pyometra is a condition of the uterus in which there are chronic inflammatory changes of the uterine mucosa characterized by sacculation of one or both of the horns and flaccid muscular walls, with little or no contractile power, owing to a loss of muscle tone. The uterus is asymetrical, abdominal in position, and one or both horns are partially filled or distended with pus. The cervix is inflamed and more or less dilated. This pathologic condition occurs most often in cows which have suffered with retention of the fetal membranes, but is known to occur when the membranes were promptly discharged after calving. In working with the bacterial flora of this condition, *Bacillus pyogenes* has been isolated in a large majority of cases. This is apparently the predominating organism in these types of infection.

The history of pyometra is usually as follows: The owner or herdsman in describing these cases states that the affected animal has not been in estrum since calving, and that a small pool of pus is usually found back of her when she is lying down. They also notice that there is more or less staining of the lips of the vulva, and collection of pus on the under surface of the tail. Cows suffering with pyometra are frequently allowed to go for six or seven months before the services of a veterinarian are employed. The treatment of pyometra, unless begun early, is often unsatisfactory, because even tho the uterus successfully completes the delayed involution and estrum is regularly established, regeneration of the mucous membrane is slow or the membrane has been destroyed or replaced by other types of epithelium. The change in epithelium interferes with or prevents attachment of the fertilized ovum; in cases in which the ovum does become imbedded, early abortions are frequent.

In cows that have had the disease only a short time, the corpus luteum will frequently be found projecting above the surface of the ovary, but in long-standing cases the yellow body will be found to be more centrally located and therefore more difficult to remove. The dislodgment of the corpus luteum in entirety is usually tho not always responsible for rapid changes in the uterus. Not only does the uterus promptly discharge its contents through the re-established muscle tone, but it also changes rapidly morphologically, regaining its symmetry and normal anatomical position within a very short time. In cases in which only a remnant of the corpus luteum is present, treatment is less successful. Estrum frequently tho not regularly appears within five days after the corpus luteum is enucleated, especially if tissue destruction has not been extensive.

CHANGES OCCURRING IN THE OVARIES

Apart from the changes occurring in the ovaries which result in the degeneration of the corpus luteum, few changes can be recognized.

Cystic degeneration of one or both ovaries within a few days after parturition has been found in several cases. The etiology of these changes has not been fully determined. In certain cases they possibly result from ascending infections, while in others the origin of the infective agent may be hematogenous. With few exceptions the described changes have been observed in purebred cattle, some of which had been conditioned for show purposes, while others were highly fed for the purpose of establishing records in milk and butterfat production. Cows which had not been prepared for either show or official testing, were found in which cystic degeneration had affected the ovaries. But in all instances, these animals had been receiving a liberal diet rich in protein. The relation of the diet to cystic degeneration is interesting and suggestive, but the lack of experimental work in this field makes it impossible to form definite opinions. Cystic changes of the ovaries, if extensive, retard involution. The uterus will regress to approximately its normal size and position, but it remains soft or flaccid, on account of failure to regain normal muscle tone. Mild inflammatory changes affecting the mucous membrane of the cervix and uterus frequently co-exist with cystic changes of the ovary.

THE CORPUS LUTEUM

The corpus luteum of pregnancy remains throughout the gestation period and from one to two months after its termination. The corpus luteum occasionally will disappear earlier than 30 days after parturition, again it will quite frequently remain for 90 days or longer. In a very large percentage of cases in which the corpus luteum persists following calving, ovulation is inhibited and the re-establishment of estrum is delayed until the corpus luteum has undergone denegeration. The relation of the corpus luteum to involution is not known, but according to Smith's Manual of Veterinary Physiology (4) the corpus luteum is suspected of secreting a hormone which aids in regression of the uterus. These various phenomena constitute the function of involution. In cows which calve normally and expel the fetal membranes promptly, regression of the uterus is quite rapid. In many such cases, the uterus will contract so rapidly that the entire organ may be placed in the palm of one's hand in 8 to 10 days after parturition. The changes in the uterine mucosa of these cows are very probably under the most favorable conditions not completed until 30 to 40 days after the termination of gestation. If the uterus is invaded with micro-organisms, both before and following the termination of the gestation period, sub-involution frequently results, and from 3 to 4 weeks will have elapsed before the uterus has regained its normal non-gravid shape, position, and muscular tonicity.

The mucous membrane of the uterus and cervix in such cases requires additional time to complete involution, as is evidenced by the discharge from the uterus of more or less mucopus which continues from 2 to 3 weeks or in certain cows may continue indefinitely, retarding or delaying involution.

BOVINE INFECTIOUS ABORTION

Infectious abortion is responsible for a very large percentage of retarded involution. Placentitis is in most instances undoubtedly due to the activities of the Bang organism, and retention of the fetal envelope is a forerunner of various disorders of the reproductive organs. Successful prevention of infectious abortion will markedly reduce the percentage of sterility, but it will not control it entirely. That sub-involution of the uterus and subsequent sterility is not always related to the Bang bacillus has been clearly shown by the research of various workers in connection with infectious abortion and sterility.

Bacillus pyogenes, various types of streptococci and staphylococci, and certain types of the colon group are frequent invaders of the reproductive organs following parturition. This fact has been conclusively shown by numerous investigators. Extensive physical trauma as a result of dystokia or resulting in the removal of the fetal membranes or in the attempt to remove them when placentitis is pronounced, is in many cases followed by metroperitonitis with multiple abscess formation. In most cases only the outer coats of the reproductive organs are involved, altho the mucous coat is frequently affected, and in cases of ovarian affection the entire gland is often destroyed and converted into an abscess which may or may not be adherent to the surrounding tissues. The abscess walls are usually very heavy with occasional exceptions of those occurring in the ovary. Adhesions of the various organs are numerous, with extensive portions of the omentum being adherent in many cases through the attempt of nature to wall off the infection.

Among the animals studied were those which belonged to the experimental herd used for the investigation of abortion disease. Several of these cows were destroyed at short intervals following parturition and the reproductive organs were subjected to a bacteriopathologic study. The findings in cases in which the examinations have been completed are included.

The following observations are reported:

CASE NO. 1

Cow calved on September 21, 1922. Calf was normal. Fetal membranes were promptly expelled. On October 3, uterus had almost completed involution. A corpus luteum was present in the right ovary.

October 23, 1922, cow was re-examined and found to be normal, the uterus had undergone complete involution. Corpus luteum of pregnancy recently terminated, present in the right ovary.

November 18, 1922. The corpus luteum in the right ovary was removed.

November 22, 1922. Appeared in estrum and was bred.

January 17, 1923. In calf, the fetus being present in right uterine cornu.

May, 1923. Serological tests negative for *Bacterium abortus* infection. Second pregnancy terminated September 12, 1923.

September 14, 1923. An abundance of clear mucus in the vagina, and the cervix would allow entrance of two fingers. Uterus had good muscle tone. Left ovary was normal. Small degenerating corpus luteum was located in the right ovary. Uterine arteries were large, tortuous, and pulsating.

September 16, 1923. Upon examination, an abundance of mucus in the vagina was discovered. The cervical canal was almost closed, and the uterus was contracting rapidly. Uterine arteries were still large and pulsating.

September 25, 1923. Vaginal mucous membrane was normal. Cervix and cervical canal were normal. Abundant amount of clear mucus in vagina. Right horn of uterus slightly larger than left, but entire organ could be gathered into the hand and only mucus was given off when massaged. Blood vessels had receded to normal size and corpus luteum had almost disappeared from right ovary. A cyst was apparently forming in the left ovary. Muscle tone of the uterus was good. Involution in this cow was rapid.

September 28, 1923. Uterus was near normal in size and position. Muscle tone was normal as manifested by vigorous contractions of the uterus when massaged. The corpus luteum in right ovary was undergoing degenerative changes and was now very small. The vagina contained a large amount of clear mucus.

October 1, 1923. Approximately normal. Clear mucus was found in vagina and cervical canal.

October 5, 1923. Cow was now normal. Involution was complete.

October 15, 1923. Animal was in season, but not bred 33 days following parturition.

November, 1923. Serological tests negative for *Bacterium abortus* infection.

CASE NO. 2

Cow calved October 29, 1922. Retained fetal membranes, which were removed manually at the end of 24 hours. Metritis was severe and extensive.

October 31, 1922. Uterus was distended four or five times normal size, inflammation active. Right cornu was flaccid and adherent to broad ligament. Right ovary partly obscured in adhesions, perimetritis present, but well circumscribed.

November 4, 1922. Right ovary hidden in adhesions near and attached to apex of right uterine cornu. Abscess in right ovary. Pus in right uterine cornu caseated and filled lumen to the extent that the walls were distended. Left ovary normal and left uterine cornu much improved, being twice the normal size. Cervicitis severe.

November 7, 1922. Extensive ovaritis and salpingitis with adhesions on right side. Right and left uterine cornua both greatly improved, but right horn somewhat distended with pus. Cervix much improved. Left ovary normal.

November 11, 1922. Uterus considerably improved. Abscess in right ovary large and adherent to the right uterine cornu and broad ligament. Left ovary normal. Cervicitis subsiding.

November 15, 1922. Abscess in right ovary greatly enlarged, approximately 12 cm. at its greatest diameter, circumscribed and adherent. Other organs improving gradually.

November 18, 1922. Condition of abscess affecting right ovary and right uterine cornu unchanged. Other organs improved. Small corpus luteum removed from left ovary.

November 28, 1922. Condition of abscess affecting right ovary and right cornu and tube, also broad ligament, unchanged.

December 16, 1922. Abscess of right ovary had increased in size, and involved the oviduct. Abscess punctured with horse trocar per vagina, and a small amount of sanious malodorous pus removed. Left ovary contained corpus luteum. Cornua of uterus normal. Abscess now pressed on bladder and caused periodical straining and frequent urination.

Serological tests positive for *Bacterium abortus* infection.

January 17, 1923. Examination revealed a large and extensive abscess involving the right ovary and oviduct, with massive adhesions. The uterus was adherent to broad ligaments, and it was difficult to outline the left ovary. Left ovary presented a condition similar to fibrosis, but was near normal in size. This cow was gaining in physical condition and there was little evidence of acute inflammation. She was slaughtered January 31, 1923.

AUTOPSY FINDINGS

On splitting open the carcass down the median line, it was noticed that there were marked and extensive adhesions in the region of the pelvis. The omental fat, rectum, uterus, ovaries, tubes, vagina, all were more or less adherent. As the paunch was pulled away, an abscess in region of right ovary was broken and the contents which poured out over intestines were semi-liquid with caseated particles. The pus was green in color and gave off a pungent offensive odor. All areas of inflammation were of a chronic nature. Parietal peritoneum on left abdominal wall shows 30 to 40 oval to circular button-like structures, the results of inflammation. These areas varied in size, from 5 to 10 mm. in diameter. There was an abundance of clear adhesive mucus in the vagina. The cervix was normal and free of adhesions. A large abscess 9 centimeters long and 6 centimeters wide was situated on the right side and attached to the dorsal surface of the vagina. The walls of the abscess were 5 to 10 mm. thick, and the pus varied in color from light gray to green. The pus near abscess wall was semi-fluid, while in the center it was caseated. The odor was pungent and offensive. A smaller abscess, 4 centimeters in diameter, was situated on inferior surface of bladder, the wall was thick, and the contents were semi-liquid and green in color. The right and left cornua, which were normal in size and appearance, were pulled sharply out of position to left of median line; they were adherent to broad ligaments and to the ovaries and oviducts. On incising the uterine cornua and viewing the mucosa, little or no evidence of inflammation was found, the carunculae were normal in appearance and size. A large irregular abscess 15 by 10 centimeters in diameter involved the right cornu, and was located at approximately 12 centimeters anterior to the bifurcation of the uterus. The abscess wall was 6 to 10 mm. across, the pus was malodorous, and varied in consistency from semi-liquid to caseous. Right ovary and oviduct were buried in adhesions and located only after careful dissection. Right ovary was normal in size, but presented a condition of fibrosis. No lutein tissue found, but one small cyst 5 mm. across and one other that may possibly have been a Graafian follicle were found. The right oviduct was enlarged to twice normal size and contained a catarrhal exudate. The left ovary and oviduct had undergone changes of cystic degeneration. The cyst was about 4 centimeters in diameter and the oviduct about the caliber of a lead pencil, with very thin walls. The fat next to the abscess formation was undergoing necrosis.

All lesions were cultured. None of them produced growths of *Bacterium abortus*. Luxuriant growths of *Bacillus pyogenes* were secured from all tissues in which there was suppurative inflammation.

CASE NO. 3

Cow calved October 10, 1922. Retained fetal membranes, which were removed manually on October 12.

Metritis, tho fairly extensive was not severe, but the discharge was quite copious. Temperature and appetite normal. Uterus possessed fairly good muscle tone. On October 16 uterus was irrigated with a normal saline solution and massage was applied. Right uterine cornu somewhat flaccid, but contracting gradually. Pus was becoming thicker and was yellow in color and somewhat malodorous.

October 31, 1922. Corpus luteum of recent pregnancy was present in right ovary. Uterus flaccid and enlarged to twice normal size. Slight pyometra. Contractions of the uterus stimulated by massage. Cervicitis was severe.

November 4, 1922. Right uterine cornu had better tone and was greatly reduced in caliber and length. Right ovary presented cystic corpus luteum. Uterus slightly flaccid, left cornu near normal, cervicitis severe with hypertrophy of external folds. Approximately 100 mils of creamy malodorous pus expelled upon application of massage.

November 7, 1922. Right ovary contained cystic corpus luteum which was not interfered with on account of extensive infection. Left uterine cornu about normal with good muscle tone. Right uterine cornu was reduced in size and not so flaccid. Approximately 50 mils of pus and mucus was discharged following massage. Uterus was irrigated with normal saline solution and then massaged.

November 14, 1922. General condition of the patient improving gradually. Cervix greatly improved.

November 18, 1922. Cervicitis still marked, uterus approximately normal. No discharge. Cystic corpus luteum removed from right ovary.

November 20, 1922. Small cyst was broken in right ovary. Corpus luteum was removed from left ovary. The corpus luteum was not located until today.

November 28, 1922. Cervix near normal. All other organs apparently normal.

December 16, 1922. Cyst in right ovary, approximate size 12 by 7 cm., was ruptured, small cyst of left ovary broken. This cow had not yet been in estrum. All other organs normal.

Bred on December 27, 1922.

Serological tests of the blood of this animal were positive for *Bacterium abortus* infection.

January 4, 1923. Corpus luteum in right ovary. No evidence of cystic formation in either ovary, cervix contains thick mucus, indicating continued presence of cervicitis.

February 23, 1923. Was in estrum. A remnant of the corpus luteum was located in right ovary. External ring of cervix was hypertrophied, but there was no evidence of acute inflammation.

February 13, 1923. In estrum and bred.

March 5, 1923. In estrum and again bred.

March 23, 1923. Cervicitis still quite extensive. Corpus luteum removed by compression from right ovary per vagina.

April 15, 1923. Cervix treated with Lugol's solution.

May 10, 1923. Treatment of cervix repeated.

May 24, 1923. Treatment of cervix repeated. Lugol's solution was used in every instance.

June 4, 1923. In estrum, cervix still slightly inflamed tho canal tightly closed. Right uterine cornu enlarged to four or five times normal size and filled with fluid. Condition resembled pregnancy. No corpus luteum in either ovary. Cervical canal dilated and an immediate escape of a thin reddish-brown fluid. This was all removed by massage, and then the uterus became ballooned with air which was removed by massage. It is possible that this cow had recently been pregnant. No signs of embryo or fetal membranes were found.

June 18, 1923. In season and bred.

Slaughtered July 3, 1923.

AUTOPSY FINDINGS

All organs were near normal except the external portion of the cervix, which was hypertrophied. The mucus membrane of the uterus was slightly congested and the carunculae were apparently somewhat enlarged. There was a corpus luteum in the left ovary. Cultures from cervix produced growth of *B. subtilis* and *Micrococcus pyogenes albus*. Cultures from the other organs remained sterile.

CASE NO. 4

Parturition occurred October 19, 1922. Dystokia, fetal and maternal, present. Calf removed by traction. Fetal membranes, retained, were removed on October 21, 1922. They were quite firmly attached, but had appearance of necrosis at placental attachments.

October 21, 1922. Uterus was contracting slowly and discharge was slight. Temperature and appetite were normal.

October 23, 1922. Uterus still greatly enlarged and actively inflamed. Left ovary normal. Unable to locate right ovary on account of perimetritis. Several pelvic abscesses in region of vagina and cervix. External cervical folds were inflamed and hypertrophied.

November 4, 1922. Uterus involuting fairly rapidly. Pelvic abscesses adherent to floor of pelvis and involving fibrous coat of vagina, were well walled in and the pus was caseated. Left ovary was normal. Cervix was greatly improved. Right ovary was still partly hidden on account of adhesions.

November 7, 1922. Abscesses in region of vagina unchanged. Uterus greatly improved, but twice normal size. Left ovary normal. Right ovary normal. Adhesions less marked. Corpus luteum had disappeared from right ovary. A scanty discharge of thick yellow pus was observed following uterine massage.

November 14, 1922. Abscesses were smaller and the general condition of the cow was much better.

November 18, 1922. A cystic left ovary was located and the cyst was ruptured. Condition of abscesses was unchanged.

November 28, 1922. All reproductive organs were apparently normal; the abscesses were smaller and three in number. They suggested the condition of fat necrosis. Those on the sides and below the vagina were flattened, with irregular surface and borders. The third, which was located partly above the vagina, was oval and the size was approximately 6 cm. in diameter.

Cow was bred on December 13, 1922.

December 16, 1922. A cystic corpus luteum was removed from the right ovary. All abscess formation with the exception of two small fibrous remnants had disappeared.

January 19, 1923. All signs of abscess formation had disappeared. Cervix normal. A second corpus luteum was removed from the right ovary. Instructions to herdsman were to breed the cow as soon as estrum appeared.

January 24, 1923. In estrum and bred.

March 23, 1923. Examined and found pregnant.

Serological tests of the blood were positive for *Bacterium abortus* infection.

This cow again gave birth to a bull calf during the night of October 9, 1923. The calf was strong and apparently normal. Blood samples collected from cow and calf at 10 a.m. October 10, 1923. At 1 p.m. an examination was made of the vagina, cervix, and uterus. The fetal membranes were still attached, with a small portion protruding through the cervical canal into the vagina. The uterus contained a large amount of thick grayish-brown but not malodorous exudate. Pregnancy had existed in left uterine cornu and the fetal membranes of right uterine cornu were not firmly attached. Placental attachments in part were necrosed, indurated, and the membranes were in places edematous. In securing placental attachments for animal inoculation purposes, it was discovered that the removal of the entire membranes could be accomplished. The uterus was irrigated with from 3 to 4 gallons of a mild antiseptic solution and the muscular contractions were found to be very rapid and strong. This was a badly infected cow according to clinical manifestations, and the placenta was the most extensively diseased one yet found. Hemorrhage of the uterus was slight, but continued for one hour.

October 11, 1923. Cow was eating well, was not straining, and only a small amount of a serosanious discharge was being expelled.

Result of agglutination tests of cow's blood positive for *Bacterium abortus* infection.

Results of agglutination test of calf's blood negative for *Bacterium abortus* infection.

October 12, 1923. Animal was eating well. No evidence of straining or discomfort. Uterus was irrigated with a normal saline solution and 2 to 3 liters of a thin reddish-brown discharge was removed. The discharge was not malodorous. Uterus had good muscle tone.

October 13, 1923. Appetite remained good. Temperature was normal. Discharge from uterus not so copious. No straining. No alteration of feces.

October 15, 1923. Feed of all kind was refused. Temperature 104 degrees F. Uterine discharge was reddish brown in color and contained shreds of placenta. Uterus was irrigated with mild therapogen solution. Tincture of nux vomica and intestinal antiseptics were given per orum.

October 17, 1923. Appetite was normal. Animal was not straining. There was no evidence of diarrhea, and the temperature was normal.

October 20, 1923. Cow was gaining rapidly in flesh and milk production, discharge from uterus consisted of thick, gray, and slightly malodorous pus. The cervical canal was partially dilated and the external cervical folds were hypertrophic. The uterus was enlarged, still flaccid, but there was evidence of contraction when massage was applied. There was a corpus luteum in the left ovary. There were no signs of infection having ascended above the uterus.

October 23, 1923. Vagina, cervix, cervical canal, and uterine cornua were rapidly approaching their normal condition. Discharge from uterus consisted mainly of mucus which contained also a small amount of pus. Muscle tone of the uterus had improved.

October 27, 1923. General condition of patient was good and milk flow had increased. There was a slight discharge of mucopus from uterus, and the uterus had good muscle tone but was still somewhat enlarged.

November 1, 1923. Condition of cow was good, no indications of any disturbances of the udder. A discharge of mucopus from the uterus had continued tho the uterus was near normal in size and position. Condition of cervical canal much improved. Muscle tone of uterus good.

November 6, 1923. With the exception of a slight discharge of cloudy mucus from the cervical canal and uterus, involution was practically completed. The uterus will probably yet undergo further reduction in size, but is apparently normal. No doubt many changes will take place in the mucous membrane before the animal will again successfully conceive. There was a corpus luteum in the left ovary. The infection did not ascend to the oviducts or ovaries.

On November 21, 1923, a corpus luteum was removed from the left ovary. The cow came in heat and was bred November 23. Estrum again appeared on December 3 when she was again bred. Estrum occurred again on January 11, 1924. On March 6, 1924, she was examined and pronounced pregnant.

CASE NO. 5

This aged cow calved August 16, 1922, and retained a small portion of fetal membranes. Metritis was not extensive or severe, the milk flow was small, appetite capricious, and back slightly arched. Uterus was douched with mild therapogen solution and massaged every third or fourth day. Uterine discharge at first was reddish brown, malodorous, and contained shreds of fetal membranes. Later it became thicker and yellow. Cervix became less inflamed, and muscle tone of uterus improved gradually.

October 25, 1922. A small cyst located in the right ovary was ruptured. A large cystic corpus luteum was removed from the left ovary. Estrum had not yet appeared. Will probably be in estrum within a few days.

October 30, 1922. In estrum and bred same day.

December 21, 1922. Partial prolapse of left vaginal wall existed. Mucous membrane of prolapsed portion was exfoliated. Large cyst in right ovary was ruptured. Cervicitis fairly extensive, other organs normal.

January 17, 1923. Portion of left wall of vagina was removed surgically. The affected wall was badly prolapsed and the mucous membrane excoriated.

January 23, 1923. Cystic corpus luteum removed from right ovary. Vagina showed induration at area of incision.

February 10, 1923. Large corpus luteum removed from left ovary. Uterus normal. A small amount of mucopus removed from the cervix. Area of operation in vagina rapidly improving.

February 14, 1923. In estrum and bred.

March 26, 1923. Examined and found pregnant in right cornu.

September 21, 1923. This animal was noticed to be ill and it was thought she was showing symptoms of an approaching abortion, and an examination of the vagina and cervix revealed the presence of reddish brown mucus and blood. Cervical canal permitted entrance of two fingers. Could not feel fetal membranes or fetus. Rectal examination indicated that uterus was empty, altho only a small portion of the uterus could be palpated. There were no signs of straining or restlessness. There was loss of appetite. Temperature elevated 2 degrees F. We believed that the fetus had been expelled in pasture.

On September 22, a thin reddish brown discharge had appeared. This was offensive. Cow still refused feed and remained down almost continuously. Examination of vagina and cervix showed these organs still unchanged. Attempted to explore and if possible douch the uterus, but failed. Attached forceps to cervix and by way of the rectum attempted to palpate the uterus, but this did not show indications that the fetus was still present. Stimulants were given, and on September 23 the uterine discharge was more copious and very offensive. A diarrhea was present at this time. A vaginal examination revealed a partially dilated cervical canal, and the presence of the fetal sacs. These were broken and after the fluids had escaped, the head of the fetus was located. The forelegs were completely retained. This condition was corrected and the fetus was finally removed by vigorous traction. It was found to be emphysematous. Odor very offensive and penetrating. Uterus was douched with mild solution of therapogen.

September 24, 1923. Fetal membranes extended beyond the vulva and were very putrid. These were removed, but not in their entirety. The uterus was irrigated and stimulants administered. Appetite better and condition of bowels improved.

September 25, 1923. Cow greatly improved. Appetite good, bowel passages normal, uterine discharge still profuse, but less offensive. Uterus irrigated with mild solution of therapogen. Temperature normal. Sample of blood secured for agglutination test.

September 28, 1923. Result of agglutination test of blood positive for *Bacterium abortus* infection.

September 30, 1923. Condition of patient unchanged.

October 1, 1923. Improving rather slowly. Appetite fair. Temperature normal. No evidence that infection will terminate fatally.

October 3, 1923.—Had developed infection in one quarter of the udder. Milk was ropy and blood-stained. Appetite fair and patient was gaining in weight. Discharge from uterus thick and grayish-white. Uterus had fairly good muscle tone.

October 5, 1923. Condition showed slight improvement.

October 8, 1923. Mastitis was quite severe. Intestinal antiseptics and tincture of nux vomica were given. Hot applications were applied to udder. Animal was gaining in flesh. Uterus was receding quite rapidly, and discharge was thick and contained mucus.

October 10, 1923. Uterus had contracted so that it was as small as the non-gravid organ. Cervix was indurated and canal was dilated. Ovaries and oviducts were normal. There was a corpus luteum in the left ovary. Vagina was normal. This cow will be released from quarantine in approximately ten days.

October 13, 1923. Cervicitis quite extensive. Left uterine cornu about normal in size, but right uterine cornu enlarged to twice its normal size, and contained eight or ten ounces of thick gray mucopus which was malodorous.

The uterus was massaged and after the pus was removed was irrigated with normal saline solution. Patient was taken out of quarantine and placed on pasture twenty-two days after parturition.

October 19, 1923. Vaginitis still acute but less extensive. External cervix was hypertrophied. Canal permitted without any difficulty the passage of a horse catheter. Mucopus in small quantities present in cervical canal and vagina. Uterus had contracted markedly and had good muscle tone, but was still slightly enlarged. By rectal palpation, small elevations probably cotyledons, could be detected. A small amount of creamy pus was removed by irrigation. Corpus luteum present in left ovary. Condition of udder had gradually improved.

October 29, 1923. A slight discharge of mucopus from the uterus persisted. Cervicitis was pronounced, and the canal was partially dilated, the left uterine cornu was slightly distended, elongated, and flaccid. Corpus luteum in left ovary was removed.

November 1, 1923. Uterus was contracted and had improved muscle tone. The uterine discharge consisted of clear mucus. The ovary from which the corpus luteum was removed was healing and showed no evidence of becoming infected.

November 3, 1923. Cow was in estrum. The discharge was clear and consisted of pure mucus. The uterus was normal in size and position and muscle tone. The wound in the left ovary had been repaired. External folds of the cervix were hypertrophied, but the canal was apparently near normal. Only one small abscess, in left uterine cornu, could be detected.

CASE NO. 6

Holstein cow calved September 7, 1922. Did not retain the fetal membranes. Appetite unimpaired. No rise in temperature. Milk flow good. Uterus douched only once with normal saline solution. Massage applied immediately after. No other treatment.

On October 25, 1922, the corpus luteum had entirely disappeared, left cornu of uterus normal, right cornu somewhat enlarged and elongated. The presence of pus was suspected but none could be massaged away. Cervix good. Fluid in vagina suggested estrum.

October 31, 1922. Uterus still somewhat enlarged but had better muscle tone. More mucus in uterine discharge.

November 9, 1922. A cyst was found in the right ovary. Left ovary was normal. Right uterine cornu was half again as large as normal, and slightly flaccid. Cervix about normal. Cyst in right ovary was ruptured.

November 15, 1922. In estrum but not bred.

November 20, 1922. Condition practically normal. Heat fluid present in vagina.

November 28, 1922. Clear fluid in vagina. Corpus luteum in right ovary was not disturbed.

Abscess in the cervical region resulting from injections of living abortion bacilli for vaccination was evacuated. This abscess was large, being 10 cm. at greatest diameter.

December 13, 1922. In heat but not bred.

December 15, 1922. Heat fluid in vagina. No corpus luteum. All organs normal.

December 21, 1922. Corpus luteum in left ovary. All other organs normal.

January 23, 1923. Corpus luteum removed from left ovary. It was recommended that this cow be bred as soon as estrum occurred.

January 25, 1923. In season and bred.

March 26, 1923. Cow was pregnant, fertilization having taken place in right uterine tube.

Gave birth to normal full-time bull calf on November 4, 1923. Fetal membranes expelled four hours later. The blood of this cow reacted positively for *Bacterium abortus* infection by both the complement fixation and agglutination tests.

CASE NO. 7

Cow calved September 12, 1922. Did not retain the fetal membranes. Appetite normal, also temperature. September 15, metritis became severe and she was placed on treatment which consisted of uterine douches and massage. Responded rapidly to treatment. September 19, involution progressed quite rapidly. Corpus luteum was disappearing. On September 20, uterine discharge consisted mainly of mucus, right uterine cornu was about normal, left uterine cornu was slightly larger than normal and elongated. Muscle tone good. On October 25, all organs were found normal and the corpus luteum had entirely disappeared. Contractions of uterus upon massage suggested that estrum was near. The blood of this cow was positive for *Bacterium abortus* infection by both the agglutination and complement fixation tests.

October 26, 1922. In estrum and bred.

January 8, 1923. Pregnant in left uterine horn. The left ovary contains corpus luteum of pregnancy.

August 3, 1923. Gave birth to normal full-time heifer calf. Fetal membranes were not retained, being expelled four hours after parturition.

CASE NO. 8

Cow gave birth to twin heifer calves, one being black and white, the other red and white. The red and white one, which was born last, was dead. The fetal membranes were partly retained, and most of these were removed manually on November 6, 1922, which was the day parturition occurred.

November 7, 1922. Remains of fetal membranes removed and uterus irrigated with a mild solution of therapogen. Muscular contractions of the uterus strong. The remaining calf died on this date and upon autopsy the true stomach was found to be greatly distended, and filled with undigested curds of milk. Lungs showed small areas of petechial hemorrhages and slight oedema near the region of the heart.

November 9, 1922. The uterus was gradually undergoing involution. Cervicitis not severe.

November 15, 1922. Uterus was irrigated with salt solution and gently massaged. Appetite was capricious and metritis very severe.

November 17, 1922. Uterus irrigated thoroly with salt solution. Metritis still quite severe and shreds of placenta were washed away. The cervix was gradually improving. Left uterine cornu and ovary were readily palpated. No corpus luteum in left ovary. Evidence obtained on palpation indicated both fetuses had been in right uterine horn.

November 18, 1922. The uterine discharge was less profuse, pus was grayish-brown in color and less malodorous. Muscle tone of uterus was improved, but involution was delayed. Left ovary was normal. A corpus luteum was present in the right ovary. Cervicitis was less severe.

November 20, 1922. General improvement was noted, both ovaries were palpated, but no evidence of disease could be found.

November 28, 1922. General improvement very noticeable, appetite good, and milk flow increased. The corpus luteum had disappeared from the right ovary. The left ovary was normal. The left uterine horn was near normal. Right uterine horn size of sausage, elongated, but muscle tone excellent. The uterus contained a small amount of pus which consisted partly of placental shreds and tissue debris. The cervix and cervical canal were much improved. The uterus was irrigated with a normal salt solution and then massaged.

January 4, 1923. Cervicitis was mild; a small amount of mucopus was obtained by massaging the uterus, the muscle tone of which was strong. Left ovary and oviduct normal. Right ovary contained large corpus luteum which was removed by pressure per vagina.

January 6, 1923. In estrum but not bred.

January 30, 1923. A newly formed corpus luteum was removed from the left ovary. All other organs were apparently normal. Estrum occurred on February 2, when she was bred.

February 27, 1923. Approximately one month after service we found a large corpus luteum, 2 cm. in diameter, in the left ovary. The cervical canal was partly open and there was an abundance of clear mucus in the cervical canal and vagina. Uterus when massaged contracted vigorously, suggesting that estrum was near. Estrum did not occur, and when examined on March 23, 1923, she was pronounced pregnant. This case was somewhat unusual in that the findings under date of February 27 indicated that fertilization had not been successful.

April 13, 1923. There was a large corpus luteum in the left ovary. Both uterine cornu were elongated, enlarged, and had good muscle tone. There were marked constrictions in left uterine cornu. She was slaughtered on this date.

AUTOPSY FINDINGS

This animal proved to be pregnant and the corpus luteum was located in the left ovary. Remains of two old corpora lutea which had been expelled surgically were found free in folds of the mesentery. They were gray in color, flattened, and soft. The blood was positive to the serological tests used in determining the presence of *Bacterium abortus* infection.

CASE NO. 9

Hereford cow gave birth to strong vigorous calf on November 16, 1922. Fetal membranes were not retained.

November 17, 1922. Cervical canal almost closed. Could insert only one finger. An abundance of mucus was found in the vagina. Uterus was involuting rapidly and had good muscle tone. A small corpus luteum in the right ovary was rapidly disappearing.

November 20, 1922. Improvement quite noticeable. Apex of right uterine horn was enlarged and firm to the touch. A corpus luteum existed in right ovary. No adhesions found. Cervical canal almost closed.

November 29, 1922. Corpus luteum in right ovary could still be determined. Involution approximately completed. Muscle tone of the uterus was good, and there was a slight discharge of clear mucus. Cervix normal. Involution in this case was quite rapid. At no time had she shown evidence of infection.

December 2, 1922. A remnant of the corpus luteum persisted in the left ovary. This structure was cystic, but was not ruptured. The left ovary and the oviducts were normal. Uterus could be placed in the palm of the hand. Involution was completed and there was an abundance of clear mucus in vagina. Cervical canal fairly well closed and free from inflammatory changes.

December 7, 1922. The cystic corpus luteum in right ovary was ruptured. All other organs were normal. The blood of this animal was negative to both serological tests for *Bacterium abortus* infection.

December 15, 1922. Heat fluid was now present in vagina. Ovaries and other organs were normal. Will be ready to breed at next estral period.

December 20, 1922. Estrum appeared and cow was bred. Was rebred on January 11, 1923.

February 15, 1923. This cow was examined and found to be pregnant.

November 1, 1923. Pregnancy terminated when she again calved successfully. The fetal membranes were expelled within four hours after calving. Involution was rapid and estrum appeared on December 1, 1923. She was served and conception resulted. A diagnosis of pregnancy was made on February 2, 1924.

CASE NO. 10

Jersey heifer gave birth to a healthy, vigorous calf on December 11, 1922. The fetal membranes were discharged two hours following parturition. December 12, 1922, examination showed that remnants of the uterine seal were still present. The cervical canal was almost closed. There was an abundance of clear stringy mucus in vagina. The muscle tone of the uterus was good, the muscular contractions being very noticeable following massage. Both uterine cornua were still enlarged four or five times. There was a corpus luteum in right ovary.

December 21, 1922. Improvement in general was rapid. The remains of a corpus luteum were located in left ovary. Uterus enlarged to twice normal size and a brownish colored mucus discharged following massage. The cervix and cervical canal were near normal. Muscle tone of uterus was normal, contractions being vigorous and rapid when massaged.

January 8, 1923. A cystic corpus luteum was removed from left ovary, but the well known signs of estrum did not develop.

January 26, 1923. A corpus luteum in the right ovary was evidence that this heifer had been in season but passed by unobserved. All other organs were normal.

January 29, 1923. Came in estrum, but was not bred.

February 21, 1923. Small cyst in right ovary, 1 cm. in diameter, was broken.

March 2, 1923. Remnant of corpus luteum was removed from right ovary and a small cyst, 8 mm. in diameter, in left ovary was broken.

March 6, 1923. Small cyst, 1 cm. A corpus luteum was removed from the right ovary. Cervix and cervical canal were normal. Fluid in vagina suggested estrum.

Blood of this cow subjected to the serological tests gave positive results for *Bacterium abortus* infection.

April 18, 1923. Corpus luteum removed from left ovary. Small cyst, approximately 1 by 1.5 cm., in right ovary was broken.

May 3, 1923. Came in season and was bred.

July 3, 1923. Cow was examined and a diagnosis of pregnancy was made.

CASE NO. 11

Angus heifer aborted. The fetus was approximately 5 months in gestation. December 14, 1922. Blood reaction to serological tests was positive for *Bacterium abortus* infection.

Was examined on December 15, and the fetal membranes had not been expelled, the attachments were very firm. Cervical canal was almost closed, the muscle tone of the uterus was normal, and the muscular contractions were pronounced upon massage. A large portion of the fetal membranes was removed and the uterus was douched with a saline solution. Very little of the mucus plug was attached to the cervical canal.

December 16, 1922. Remnants of a corpus luteum in each ovary. Uterus was contracting rapidly, and muscle tone was normal. Remnants of placenta and tissue debris were removed by irrigation and massage.

December 21, 1922. Uterine contents greatly diminished, not malodorous, and large quantities of clear mucus were being discharged. Applied massage to ovaries and uterus. Uterus possessed normal muscle tone.

January 10, 1923. Bred.

February 15, 1923. Examined for pregnancy. Diagnosis, possibly pregnant.

March 31, 1923. Estrum appeared and cow was rebred. She proved to be not in calf.

April 25, 1923. Estrum occurred and she was again rebred.

June 22, 1923. There was cessation of estrum on account of a retained corpus luteum. She was examined for pregnancy and found not to be pregnant. The corpus luteum in the left ovary was removed. Estrum occurred on June 24, when she was bred. On August 15, was pronounced to be in calf. This pregnancy terminated February 27, 1924. Calf was premature but was active and vigorous. Fetal membranes were expelled promptly but placental necrosis was extensive. Smears prepared from the placenta revealed the presence of organisms which were believed to be *Bacterium abortus*.

CASE NO. 12

This was a purebred cow affected with mummification of the fetus. The dessicated fetus was located in the right uterine cornu. The left ovary was enlarged and slightly cystic. A corpus luteum in the right ovary was located. Fetus was about the size of a cat and the cow was within two weeks of termination of her gestation period. The corpus luteum was removed by pressure per vagina. On the second and third days following the operation the cow was bellowing and acting as though she had calved. An examination on the third day revealed the presence of the fetus engaged in the vagina and cervical canal. The fetus and genital tract were very dry and some traction was necessary for its removal. Three weeks later the uterus and all other organs were apparently normal, muscle tone of the uterus was normal, and clear mucus in the vagina suggested estrum. Estrum appeared and the cow was bred twenty-five days after the operation.

January 6, 1923. Corpus luteum in left ovary. All organs were apparently normal.

January 19, 1923. Cow had passed over one heat period.

March 10, 1923. Examined for pregnancy. Diagnosis, pregnant.

September 7, 1923. Animal aborted and retained the fetal membranes. Sample of her blood subjected to the agglutination test was positive for *Bacterium abortus* infection.

February 22, 1924. Again in calf.

CASE NO. 13

Parturition occurred on December 20, 1922. Fetal membranes were expelled three hours later. Examined December 21, 1922. and involution was found to be progressing rapidly.

December 29, 1922. General condition much improved. Muscle tone of uterus normal. No cervicitis. Corpus luteum still present. Uterus approximately normal in size and position.

January 17, 1923. With the exception of a small cyst, approximately 1 cm. in diameter, in left ovary, which was ruptured, all other organs were apparently normal. The blood was positive to the serological tests employed in determining the presence of *Bacterium abortus* infection.

January 24, 1923. In season and bred.

February 14, 1923. In season and bred.

March 8, 1923. In season and bred.

April 1, 1923. In season and again bred.

June 22, 1923. Examination showed that the animal was now pregnant.

CASE NO. 14

Cow was delivered of a large bull calf on December 27, 1922. The animal was suffering with uterine inertia and while the cervical canal was dilated and the fetus was in normal position, no effort was being made to expel it. Two mils of pituitrin was given subcutaneously at the noon hour. At 1:00 p.m. there was some evidence of labor, but she made only slight progress. We then applied traction and secured a big strong calf. Fetal membranes were tightly attached. Fetal membranes were not retained, having been expelled six hours later. All four legs of the cow were edematous before parturition and remained filled for forty-eight hours following calving. The cow was constipated, with complete loss of appetite and elevation of temperature to 106 degrees F. Metritis was apparently mild. Saline purgative given, also potassium acetate in capsule. Tonics and intestinal antiseptics (creolin and mucoseptone) were also given.

January 2, 1923. Metritis and cervicitis mild, chocolate brown discharge from the uterus upon the application of massage. Corpus luteum had disappeared. Both horns of uterus were enlarged five or six times the normal non-gravid size. Temperature was normal, appetite had improved, and milk flow was gradually increasing.

January 4, 1923. Uterus contracting slowly. Left ovary enlarged. Its greatest diameter was 9 or 10 cm. Was possibly in process of abscess formation. Oviduct was adherent and enlarged. Cervicitis existed in mild form. Uterus was douched with normal saline solution. Appetite was normal, milk flow had increased, and temperature was normal.

January 13, 1923. Left ovary and oviduct almost normal in size. The corpus luteum had disappeared. Left uterine cornu had good muscle tone and was near normal in size. Right uterine cornu was still enlarged about three times its normal size, and the walls were flaccid and showed lack of muscle tone. Four or five necrosed maternal cotyledons were removed by irrigation and five ounces of thick grayish mucopus was also removed. The cervix and cervical canal were near normal.

January 17, 1923. A small amount of mucopus in the vagina, and inflammation of cervix less severe. The muscle tone of left uterine cornu was near normal, right uterine cornu was enlarged and distended with pus, which was not malodorous. Cervical canal was very tortuous, making the passing of a catheter very difficult. Irrigations and massage of the uterus brought forth one half liter of mucopus. Corpus luteum had become absorbed.

January 19, 1923. Cow showed marked improvement. Uterus now had good muscle tone and was less flaccid, but was still discharging a small quantity of mucopus. Uterus irrigated and massaged. Cervicitis less severe. Pus removed from uterus was thick, grayish yellow and mixed with mucus.

January 23, 1923. Uterus was still flaccid but had better tone. A small amount of mucopus was obtained upon massage and one degenerated maternal cotyledon was expelled. The cervix was inflamed and the canal was difficult to follow. Small cyst in right ovary was ruptured, left ovary was probably free of cysts or lutein tissue. Uterus was massaged and irrigated with mild solution of therapogen.

January 26, 1923. The cervix remained unchanged. Yellowish-gray pus mixed with mucus was obtained upon massage and irrigation of the uterus. The uterus was flaccid, had poor muscle tone, and contracted only slightly when massaged. A small cyst in the left ovary was ruptured. Serological tests positive for *Bacterium abortus* infection.

January 31, 1923. Cervicitis was less severe. The left uterine cornu was still flaccid with poor muscle tone. Two ounces of thin grayish offensive pus was secured upon massage. A small cyst, 1.5 centimeters in diameter, in left ovary was broken. No evidence of lutein tissue in either ovary. Uterus was irrigated with hot saline solution and massaged vigorously.

February 5, 1923. Cervicitis now very mild. Very little pus found upon massaging uterus. Ovaries and uterine tubes normal.

February 16, 1923. Involution completed. Uterus was free of pus and all organs were apparently normal in position, size, and contour.

February 27, 1923. Animal was killed and found free of gross changes or alterations of the reproductive organs. Cultures from the various organs remained sterile.

AUTOPSY FINDINGS

The wall of the right cornu was 8 mm. thick, while the wall of the left cornu was 1 cm. thick. The cervix was 11 cm. long and the mucous membrane appeared normal. The mucous membrane at the beginning of the body of the uterus was reddish brown in color and had the appearance of being hyperaemic, serous surface of cornua congested. The carunculae in left cornu were 2 cm. by 1 cm. Carunculae in right cornu were 8 mm. by 5 mm. The entire mucous membrane of both cornua was reddened and swollen, more pronounced in left than in right cornu. Both ovaries were normal in size and contained in cortical region several follicles of various sizes. The right ovary showed on the surface a small wound containing blood, which indicated that this animal had recently ovulated. The oviducts were normal in size and position.

CASE NO. 15

This cow gave birth to a heifer calf on January 14, 1923. Fetal membranes were expelled within twelve hours.

January 15, 1923. The vagina was found to be injured as tho torn during delivery. Cervical canal was almost closed, but some of the mucous plug of pregnancy was still intact. Uterus had contracted fairly rapidly and possessed good muscle tone. Serological tests were positive for *Bacterium abortus* infection.

January 17, 1923. Right vaginal wall just inside vulva quite badly injured but the wound did not extend into the fibrous coat. A large blood clot filled the wound but it was not interfered with.

January 23, 1923. Lacerated part of vagina showed the beginning of necrosis. Small part of serous coat of rectum adherent to roof of vagina. Uterus was contracting fairly rapidly. Vagina was douched with a hot saline solution.

January 26, 1923. Examination showed vaginitis to be less severe. Small pieces of the vaginal mucous membrane had sloughed away. Manual vaginal and rectal explorations caused pain, which was evidenced by severe straining. Vagina was douched with hot saline solution.

February 5, 1923. Vaginitis and cervicitis were less severe, and corpus luteum had disappeared. The uterus was found to contain a small amount of pus, was massaged and irrigated with a mild solution of therapogen.

February 16, 1923. Animal now in good condition, all organs being apparently normal.

March 5, 1923. Cow was in estrum and bred.

April 6, 1923. A diagnosis of pregnancy was made, she was then slaughtered and found pregnant, conception having occurred in left uterine cornu. Corpus luteum of pregnancy present in left ovary.

CASE NO. 16

A purebred Jersey cow gave birth to a strong and healthy bull calf on January 28, 1923. Calving occurred at 8:30 p.m. Fetal membranes were expelled at 11:45 p.m.

January 29, 1923. The uterus was contracting rapidly and the cervical canal was almost closed. A small portion of the mucus plug was found clinging to the external cervical folds, which were hyperaemic and hypertrophic. Uterine blood vessels were full and pulsating. A corpus luteum was present in the right ovary.

February 10, 1923. Corpus luteum persisted in the right ovary. An abundance of reddish brown mucus was being discharged from the uterus. External portion of cervix was hypertrophic, muscle tone of uterus strong, tho uterus was enlarged 4 to 5 times. The right uterine horn was the larger.

February 2, 1923. Calf became ill with a violent form of white scours.

February 4, 1923. Calf died. Cultures made from the lungs developed a few colonies of *B. coli.* All other tissues cultured proved sterile.

The cow was examined again on February 21, 1923, when a large corpus luteum was found in the right ovary. The cervix was much smaller and almost normal. The uterus was normal in both position and conformation.

Indications were that this cow would suffer delayed estrum unless the corpus luteum rapidly degenerated. Conditions would have justified one in calling this a retained corpus luteum, and it would in all probability have to be removed. Serological tests negative for *Bacterium abortus* infection.

March 26, 1923. The corpus luteum had disappeared from the right ovary, but the symptoms of estrum had not been observed. On April 10, 1923, a newly formed corpus luteum in the left ovary was removed and the herdsman was instructed to watch closely for signs of estrum.

April 14, 1923. In season and bred.

May 23, 1923. A diagnosis of pregnancy was made. Corpus luteum of pregnancy was present in left ovary.

Pregnancy terminated January 23, 1923, when a strong, vigorous, 62-pound calf was born. Fetal membranes were promptly expelled. Parturient paresis developed on January 24, but a good recovery was made. Involution was rapid and the general physical condition was good. Examination on March 1 showed that the estrous cycle had not yet been re-established and that the corpus luteum was retained. Estrum appeared March 3, at which time the animal was bred. The corpus luteum of the recent pregnancy was still retained. This cow is fourteen years of age and has been at University Farm since 1915. During this period she has calved successfully nine times. She has twice been affected with parturient paresis, the first attack occurring in the summer of 1915.

CASE NO. 17

Cow showed signs of abortion on January 28, 1923. Physical examination revealed the presence of amniotic sac engaged in cervical canal and vagina. Cervical canal was well dilated but uterus was more or less inert so far as muscular contractions were concerned. The fetus was presented posteriorily, was edamatous and dropsical. Fetal membranes were filled with gelatinous fluid and two to three inches through. Abdominal cavity of fetus was filled or distended with sero-gelatinous fluid. Stomach contents consisted largely of what was apparently a semi-liquid mucus. The fetus was approximately six to six and one half months in development. The cow was badly shrunken, very thin, and the appetite was capricious. There was a painful swelling of the right front carpal joint. This condition, together with an acute attack of indigestion was first noticed on January 26, 1924.

Examination on January 29, 1923, presented the following symptoms: Temperature normal, inappetance, feces soft and covered with mucus. The animal was gaunt, but not depressed. Was not straining, altho the fetal membranes were still attached. Entire attachment confined to left cornu. Right cornu involuted to the extent that only two fingers could be inserted into the lumen. The cotyledons in the non-gravid horn could not be palpated. In douching the uterus, muscular contractions were stimulated, so that the hand could not be removed until the organ relaxed. A small corpus luteum persisted in left ovary. Cervical canal closing slowly.

Stomach contents of fetus cultured for *B. abortus* Bang and a luxuriant growth was secured in pure culture. Cultures of dropsical fluid remained sterile.

January 31, 1923. Cervical canal was closed to the extent that it would allow the passage of only two fingers. Right cornu was almost back to normal size and the fetal membranes were apparently not attached in non-gravid cornu. Neither were the carunculae markedly enlarged. Fetal membranes were still very firmly attached in left cornu and the muscle tone of this part was very good. Apex of left cornu was turned up along side body of uterus and when palpated was very tense and sensitive. Both ovaries were palpated and there was no sign of a corpus luteum in either ovary. Uterus was irrigated with four gallons of a normal salt solution. Temperature was normal, but the appetite remained poor. Rumination had ceased and the feces were hard and scanty. Laxatives and tonics were administered.

February 1, 1923. Cervical canal was open but would allow the passage of only a small catheter. No evidence of severe cervicitis. Right uterine cornu was almost normal in size and position. Both ovaries were palpated and found to be free of corpora lutea. Muscle tone of uterus was improved and after irrigating with hot saline solution a piece of placenta was secured and with traction aided by massage of the uterus, the fetal membranes were removed. The apex of the left uterine horn was firm and contracted vigorously when massaged. Tonics and laxatives were again given. Temperature was normal. Appetite was more or less capricious.

February 5, 1923. General improvement of animal was noticed. Uterus was massaged and irrigated with normal salt solution. Serological tests were positive for *Bacterium abortus* infection.

February 10, 1923. Animal showed marked improvement. Uterus near normal in size and position. No corpus luteum in either ovary. Cervicitis was less severe. Small amounts of mucopus were being intermittently discharged. Emaciation was pronounced but appetite was greatly improved. Uterus was improving. Two hundred and fifty mils of thick creamy pus was removed from the uterus by massage. The pus was thick, grayish-yellow, and malodorous. Condition of cervicitis was improving, but improvement was slow.

February 19, 1923. A large corpus luteum was removed from the right ovary. This corpus luteum was either deeply situated in the ovary and in this way passed or escaped detection until this date; or the cow ovulated and a new corpus luteum resulted, as is the regular procedure. The latter explanation is probably not correct, but it seems almost impossible repeatedly to mistake or overlook a corpus luteum of that size, even tho it was deeply imbedded. The uterus was near normal in size and position, had fairly good muscle tone, and gave off only a small amount of mucopus upon massage. The cervix was near normal.

March 2, 1923. Two small cysts, approximately 8 mm. in diameter, located in each ovary were broken. The one in the right ovary formed where the corpus luteum was removed on February 19. Cervix was normal. Uterus had good tone, was free of pus formation, and the animal was improving rapidly. She was gaining weight, increasing in milk production, and was eager to exercise.

March 6, 1923. Cervix and cervical canal now normal. Mucus containing particles of pus located in the vagina. There were six cysts, approximately 0.5 to 1.5 centimeters across, located in the ducts of Gärtner. Uterus, ovaries, and tubes were normal. Muscle tone of uterus was good.

March 14, 1923. In season and bred.

April 16, 1923. In season and bred.

June 17, 1923. In season and again bred. On July 30 living abortion vaccine was injected and on September 27 was rebred. On November 15 she was pronounced in calf.

CASE NO. 18

This heifer aborted twin fetuses on March 29, 1923, male and female approximately six months in gestation. Fetal membranes were dropsical and fairly firm at points of attachment. A large portion of fetal envelopes was removed on March 30, 1923, and the uterus was irrigated with normal saline solution.

March 31, 1923. Uterus was again irrigated and a small portion of fetal membranes was removed. Muscle tone of uterus was strong and cervical canal was gradually closing.

April 2, 1923. Uterus was irrigated and gently massaged. Muscle tone was near normal. Uterine discharge was reddish-brown and malodorous. Animal gradually improving, appetite only fair, but there was no straining and the back was not arched. Serological tests were positive for *Bacterium abortus* infection.

April 19, 1923. In estrum. Muscle tone was good. Heat fluid was abundant but contained small particles of pus. Cultures were negative for *Bacterium abortus* Bang. No corpus luteum in either ovary.

May 4, 1923. In estrum and bred.

May 30, 1923. In estrum and bred.

June 15, 1923. Was rebred, after which there was cessation of estrum until September 10, when it again occurred. At this time there was a small cyst in left ovary. The cyst was ruptured and on September 27 she was rebred. Experimental animal inoculated with placental extract was negative to *Bacterium abortus* infection.

November 5, 1923. Cow was examined and pronounced pregnant.

CASE NO. 19

A heifer gave birth to a bull calf on June 6, 1923. Presentation anterior. The fore feet extended with lateral deviation of the head. Fetus was removed with considerable traction after presentation was corrected. This calf had prominent goiter. Blood samples were collected from both calf and dam, also a sample of milk and a small portion of placenta. Blood of both cow and calf was negative to serological tests for *Bacterium abortus* infection. The milk as well as the animal inoculated with placental extract was negative for *Bacterium abortus* infection.

June 8, 1923. A portion of the fetal membranes was removed.

June 9, 1923. The vagina was irrigated with mild antiseptic solution. Tonics and intestinal antiseptics given per orum.

June 11, 1923. The vagina was irrigated and tonics and intestinal antiseptics were again given per orum. Pathologic changes now were vaginitis, metritis, and enteritis, the latter being evidenced by profuse diarrhea. There was inappetance and the temperature was elevated to 104 degrees F.

June 12, 1923. Uterus was irrigated with a hot saline solution. Muscular contraction of uterus was more vigorous, altho there was active inflammation of a severe type. A portion of fetal membranes was still retained, and an offensive odor was given off with the uterine discharge. Condition of vagina was improving. Temperature 103 degrees F. Appetite fair, and no further evidence of diarrhea. Tincture of nux vomica and an intestinal antiseptic (creolin) were again given per orum.

June 13, 1923. Vagina irrigated with hot saline solution and uterus gently massaged. Condition of uterus improving. Vagina also improving. No signs of diarrhea. Feces were normal. Appetite fair. Nux vomica and intestinal antiseptics were continued.

June 15, 1923. Paravaginal abscesses, two in number, were located. The one on the right side was approximately 14 by 10 cm., that on the left side, 10 by 6 cm. The contents of abscesses were caseated and the walls were apparently very heavy. Cervicitis severe, uterus flaccid, muscle tone poor with little or no contraction. Contents of uterus were liquid in consistency, reddish brown in color, and gave off a very offensive odor. Involution was seriously delayed. Diarrhea had been controlled. Uterus was massaged but not irrigated. Small portion of fetal membranes still retained and a few of the cotyledons could be palpated.

June 18, 1923. Paravaginal abscesses have receded to one half maximum size attained, and very hard. Uterus contracting fairly rapidly, and the remaining fetal membranes had been expelled.

June 23, 1923. Contraction of uterus continued to be rapid. Uterine discharge consisted mainly of mucus. Cervical canal was near normal. Injuries of the vaginal mucous membrane have been entirely repaired. Abscesses have almost disappared, having terminated in small indurated areas.

June 27, 1923. Posterior third of vagina was constricted as a result of the injured mucous membrane. Cervical canal was apparently normal. The apex of the right cornu was adherent to the oviduct and ovary. These structures were adherent also to the broad ligament and omentum. Both cornua were approximately normal in size and there was no evidence of infection having involved the left ovary and oviduct.

July 3, 1923. Animal was killed and autopsied.

AUTOPSY FINDINGS

The uterus had almost attained its normal non-gravid size and position. The left uterine cornu was still slightly enlarged and elongated. The right cornu was at the apex adherent to broad ligament, oviduct, ovary, and omental fat. Three small abscesses, approximately one cm. in diameter, on dorsal surface of wall of right cornu, and adherent to the muscle below and the fat above. Oviduct contained pus and was partly buried in adhesions. Right ovary was buried and slightly cystic. No corpus luteum in either ovary. No lesions in left ovary. Uterine mucosae slightly reddened and covered with a small amount of mucopus. Carunculae in each cornu were about of equal size, those in left being the larger and more prominent. The left oviduct was normal, there being no evidence of cervicitis. Vaginal mucous membrane normal. Peri-vaginal abscesses small, walled off, and partly surrounded by fat necrosis. The pus in all the abscesses was yellowish-green, pasty, and malodorous. The animal suffered with placentitis and severe injury of the vaginal mucous membrane. The left ovary was normal and showed no signs of lutein tissue.

Results of bacteriologic examination: Abscess involving right ovary and oviduct gave growth of *B. coli communior.* Left ovary and oviduct gave growth of *Staphylococcus pyogenes albus.* Peri- and paravaginal abscesses gave growth of a streptococcus and *B. coli communior.*

SUMMARY

Involution consists of numerous and interesting phenomena, the most important of which is the reduction in size of the uterus. The act of involution offers a barrier to infection, but when sepsis occurs involution is stopped or retarded. The uterus which regresses rapidly in size and possesses normal muscle tone does not readily absorb bacteria or their products. In cows in which the act of parturition is normal and the fetal membranes have been promptly expelled, regression of the uterus as a rule is very rapid. The uterus will in many cases resume its non-gravid position and morphology within 10 days. However, in a large number of cows which have apparently calved normally in every way and which to all appearances do not develop infection, 2 or 3 weeks are frequently required before the uterus is completely reduced.

The entire amount of time required for the completion of the various phenomena of involution varies from 30 to 40 days.

The relation of the corpus luteum to involution is not known, but in certain cases of uterine affection, particularly pyometra, in which involution is retarded or entirely stopped, the early removal of the corpus luteum is followed by vigorous muscular contraction of the uterus, resulting in evacuation of its contents and restored normal function of the reproductive organs.

Retention of the fetal membranes is a serious menace to involution, and not only produces subinvolution, but seriously interferes with the immediate health of the cow and endangers her ability again successfully to reproduce.

Bacterium abortus Bang is capable of producing extensive and severe placentitis with infiltration and oedema of the chorion.

Retardation of involution as a result of sepsis, which may affect not only the uterus but the oviducts and ovaries as well, is usually due to pyogenic bacteria. In these cases suppurative inflammation is not uncommon.

Among the organisms frequently found are the *Bacillus pyogenes,* Staphylococci, Streptococci, *B. coli,* and other pyogenic organisms.

Successful control of bovine infectious abortion will mean a greatly reduced percentage of cases of retained fetal membranes, which in turn will reduce the cases of subinvolution and subsequent disorders of the reproductive organs resulting in either temporary or permanent sterility.

ADDENDA

CASE NO. 1

A second calf was born on September 12, 1923. She was bred 33 days following parturition, and calved again on September 9, 1924. Estrum occurred on October 1, at which time she was bred. Signs of estrum again appeared on October 21, and the cow was rebred. On January 22, 1925, this animal was pronounced as being with calf.

CASE NO. 4

This cow again calved at term on August 26, 1924. Placentitis was severe. The fetal membranes were retained. Only slight areas of necrosis of the placental and interplacental tissues were observed. The inflammatory changes later extended to the serous coat of the uterus, which resulted in loss of appetite, elevation of temperature, and rapid emaciation. Treatment was administered regularly until October 7, 1924, when the patient had recovered. Extensive lesions of the left ovary and oviduct together with numerous adhesions, led us to believe that her fertility would be greatly reduced, if not entirely suspended. The cow was slaughtered on October 30, 1924.

AUTOPSY FINDINGS

Massive adhesions involving the uterus, vagina, bladder, rumen, and omentum. A large abscess involved the left ovary. The left oviduct was buried in adhesions and difficult of recognition. Numerous small abscesses were present in the muscular and serous coats of the uterus. The right ovary was cystic while the right oviduct was apparently normal. The mucous membrane of the uterus was normal. The mucous membrane of the uterine cervix showed the presence of chronic inflammatory changes. This cow was rather remarkable in that she calved successfully three times, tho each gestation was accompanied by extensive placental disease.

CASE NO. 5

This cow reacted to the tuberculin test and was slaughtered November 20, 1923.

CASE NO. 6

This cow is now in calf and is due to freshen in April, 1925.

CASE NO. 7

Cow calved again successfully October 28, 1924. She is at the present writing again with calf.

CASE NO. 9

Parturition again occurred on October 1, 1924, and at the present time she is with calf.

CASE NO. 10

Was sold October, 1923. Cow was pregnant.

CASE NO. 11

This cow gave a positive reaction to the serological tests used in the diagnosis of abortion disease. Involution was completed in approximately twenty days. This animal was considered as being especially dangerous as a spreader, and as her breeding and conformation were not particularly desirable, she was sold for slaughter.

CASE NO. 12

During September, 1924, it was discovered that the fetus had succumbed and was undergoing the process of mummification. Removal of the corpus luteum resulted in expulsion of the dessicated cadaver. Involution progressed in a normal manner and at the present time she is again in calf.

CASE NO. 13

Cow again calved successfully on January 5, 1924. Fetal membranes were expelled promptly. A few months later this cow suffered a severe injury to the left hock joint and was later sold for slaughter.

CASE NO. 16

Parturition occurred again on December 8, 1924. A small portion of the fetal membranes was promptly expelled, but the remaining portion, owing to placentitis, was very firmly attached. Failure to expel the remaining membranes retarded involution, and the inflammatory changes involving the uterine mucosa extended into the muscular and serous coats. The result was inappetance, elevation in temperature, stiffness of gait, and mastitis. Recovery was slow, but estrum occurred in March, 1925, at which time she was considered to be in fair physical condition.

CASE NO. 17

Normal parturition occurred in August, 1924. The fetal membranes were retained and were removed manually 48 hours later. Involution was retarded. Inflammation of the uterus became very extensive and finally was complicated with a severe form of mastitis. Emaciation was progressive and as the entire udder was so extensively involved with inflammatory changes, particularly abscessation, it was deemed advisable to slaughter.

AUTOPSY FINDINGS

The cow was destroyed in November, 1924. The reproductive organs were normal in appearance. The uterus so far as could be determined macroscopically had completed involution. The gland tissue of the udder was markedly atrophied, small areas of necrosis were numerous, and many small abscesses were found in various portions of the udder.

CASE NO. 18

Estrum appeared in March, 1924. A physical examination showed that conception had not resulted from the September service, altho an early abortion may have occurred. Cystic degeneration affecting both ovaries developed soon after the signs of heat and altho treatment was applied at regular and frequent intervals, the patient gradually became a nymphomaniac. She was condemned as incurably sterile and was sold for slaughter.

ACKNOWLEDGMENT

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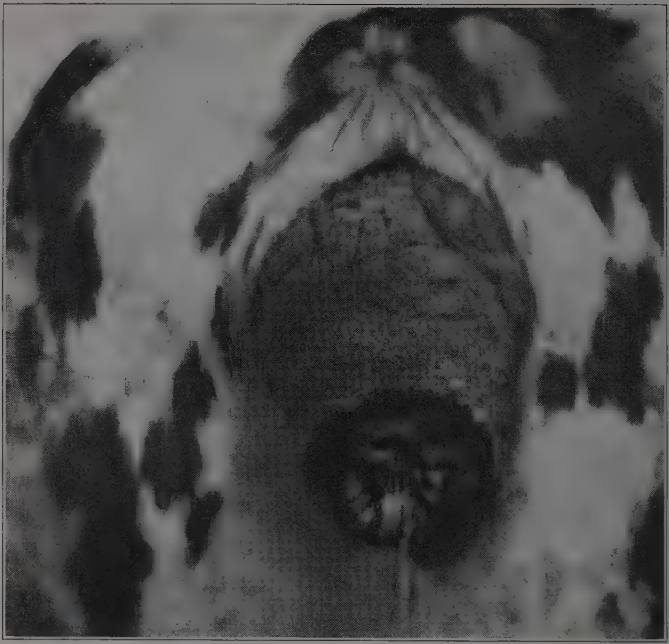

Fig. 1. Prolapse of the Vagina

The hypertrophic folds of the external Os of the cervix are shown in the center. The cervical canal is dilated and a mucus discharge can be seen clinging to the edge of the Os.

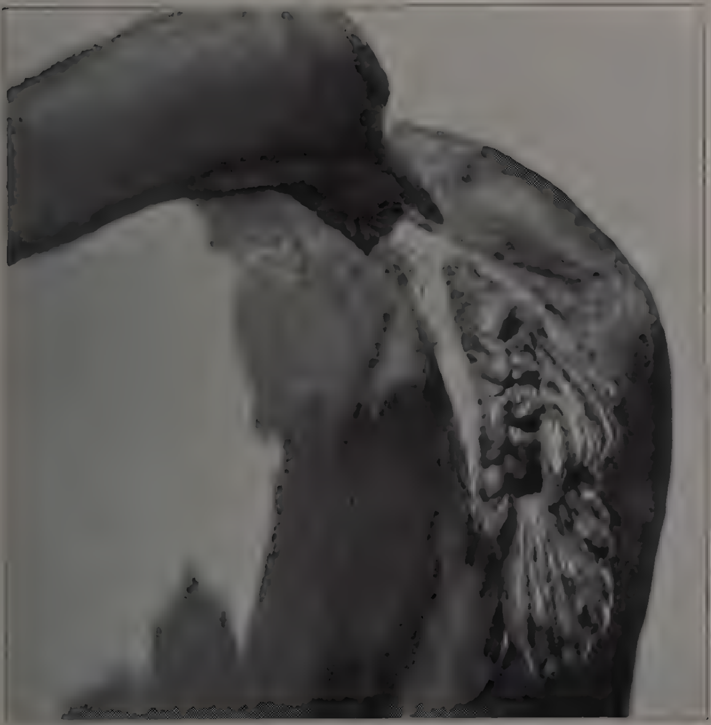

Fig. 2. Chronic Cervicitis

The external Os of the cervix is prolapsed and is markedly hypertrophied. The cervical canal is dilated and there is a copious discharge of mucopus.

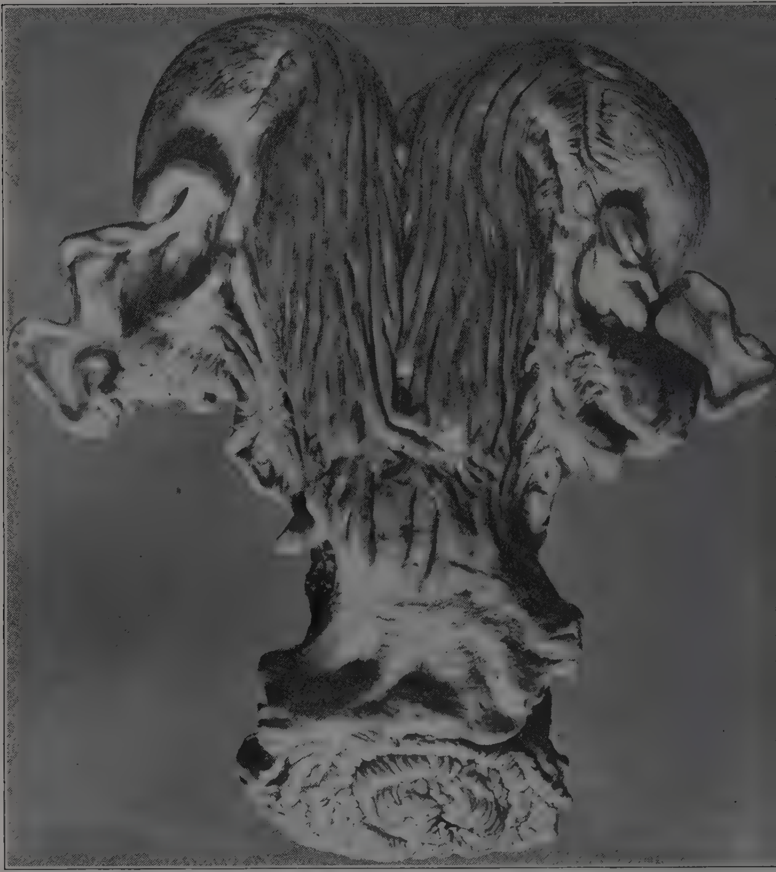

Fig. 3. Uterus Showing Final Stages of Involution

The deep longitudinal furrows of the muscle are clearly shown. A corpus luteum which projects above the surface can be seen in the right ovary.

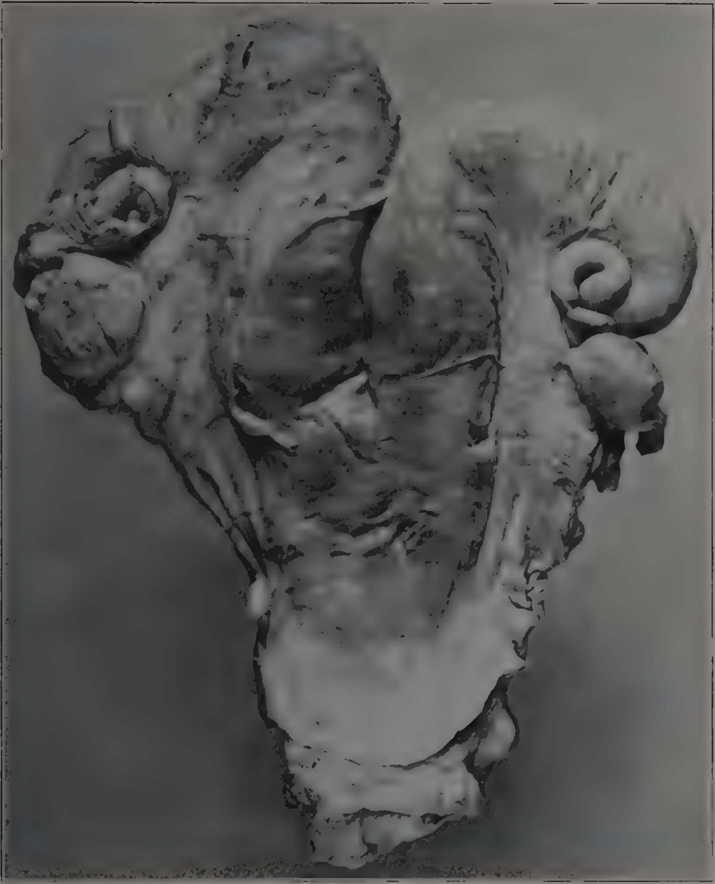

Fig. 4. Acute Metritis of a Severe Type, in Which the Inflammation has Extended to the Muscular and Serous Coats

Extensive adhesions involve the left uterine cornu, tube, and ovary.

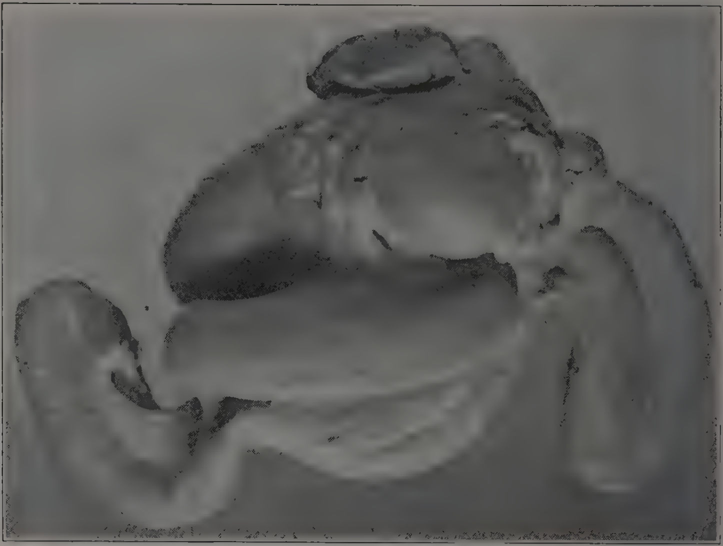

Fig. 5. Uterine Tube or Oviduct Showing Condition Known as Hydrosalpinx

This is the result of an acute inflammatory process, which is characterized by pus formation. The pus is absorbed and replaced by a clear watery straw-colored fluid. The tube is enlarged, very tortuous, and thin-walled. Adhesions are extensive.

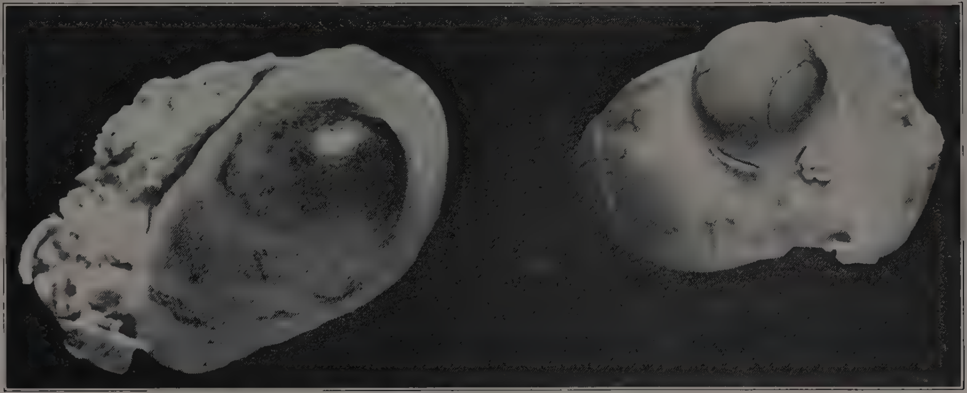

Fig. 6. Ovaries Showing Presence of Corpora Lutea

The ovary on the right shows two yellow bodies both of which project above the surface. Small blood vessels on the surface of these structures are plainly shown.

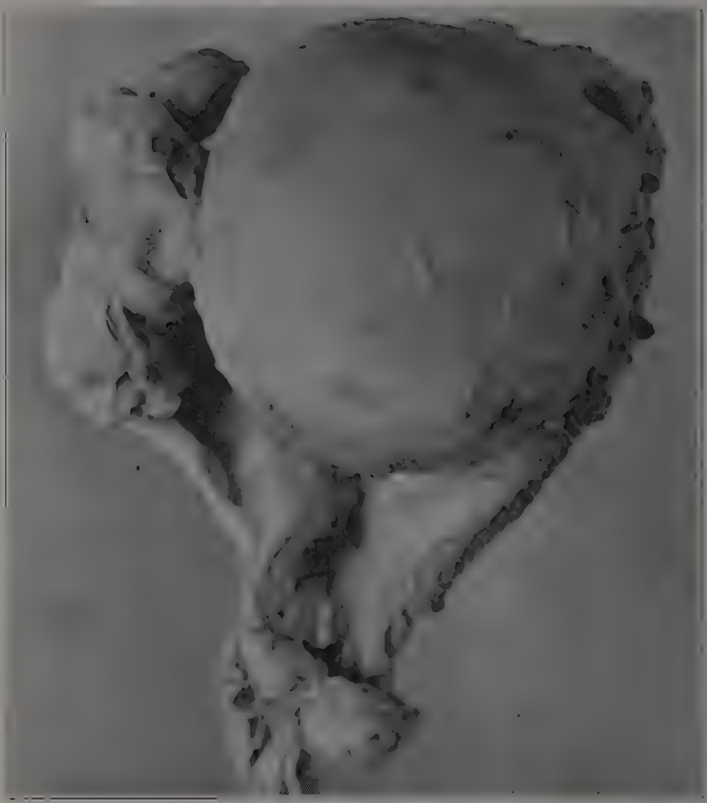

Fig. 7. Ovary and Oviduct Affected With Suppurative Inflammation

The ovary has been converted into a large abscess. The abscess wall is not especiall thick but is more dense than the wall of the ovary which is cystic. Massive adhesions hav obscured the greater part of the oviduct.

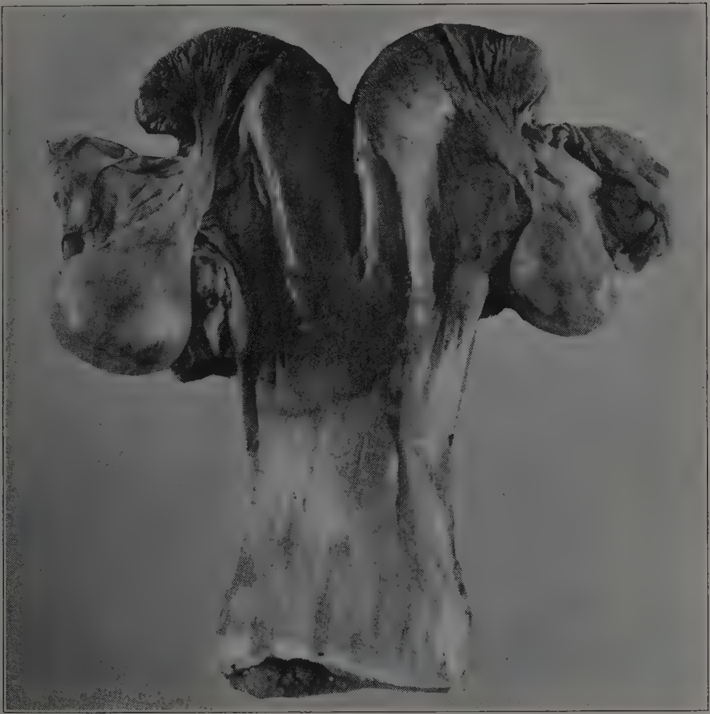

Fig. 8. Genital Organs, Showing Presence of Inflammation of Uterus and Cystic Degeneration of the Ovaries

The ovaries are greatly enlarged and contain a clear watery fluid. The ovarian walls are thin and as a rule can be easily ruptured.

TECHNICAL BULLETIN 24 AUGUST, 1924

The University of Minnesota
Agricultural Experiment Station

Observations of the Effect of B. abortus Bang on the Weight of the Spleen of the Guinea Pig

C. P. Fitch and R. E. Lubbehusen
Division of Veterinary Medicine

UNIVERSITY FARM, ST. PAUL

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OBSERVATIONS OF THE EFFECT OF B. ABORTUS BANG ON THE WEIGHT OF THE SPLEEN OF THE GUINEA PIG

C. P. Fitch and R. E. Lubbehusen

The use of small animals has played an important rôle in the isolation, study, and ultimate identification of pathogenic organisms in investigations of human and animal disease. Many advancements in our knowledge of disease have depended largely upon the utilization of the guinea pig and rabbit as means of study. Such study embraces the observation of the direct effect of the disease process upon the laboratory animal during life; or the examination of postmortem lesions, both gross and microscopic, together with recovery of the disease-producing organism for subsequent identification.

In our investigational work of bovine infectious abortion, guinea pig inoculation has been an invaluable aid from the standpoint of both diagnosis of infection and isolation of the organism for study from a variety of sources. As *B. abortus* Bang infection in guinea pigs does not usually manifest itself in any striking manner during life, the ultimate diagnosis of such infection has depended thus far upon serologic tests and the isolation of the organism by the direct culture method.

Many investigators have described postmortem lesions which have been observed in known cases of *Abortus* Bang infection in guinea pigs. Fabyan(1), in his studies of the pathogenesis of *B. abortus* Bang, describes in detail the gross and microscopic pathological changes of various organs of guinea pigs so affected. Schroeder and Cotton(2) observed certain lesions in guinea pigs resulting from the injection of milk which in many instances were confused with tuberculosis, until bacteriologic examination showed the causative organism to be *B. abortus* Bang. Smillie(3) has recorded in some detail the postmortem lesions found in guinea pigs inoculated with abortion-infected material from a variety of sources, and concludes: "Inoculation of guinea pigs with *B. abortus* Bang is regularly associated with an enlarged congested spleen. Other less constant lesions affect the testicles, kidneys, liver and bones." Further "The spleen is the organ in which the bacteria are regularly present and in large numbers. Cultures must be made from it to insure success." Meyer, Shaw, and Fleischner(4), in their study of the comparative pathogenicity of *B. melitensis* and *B. abortus,* conclude in part: "Experiments extending over several years support the well known fact that *B. abortus* may produce in guinea pigs an interesting inoculation disease. However, the degree of tissue injury in the spleen and lymph nodes may vary considerably." A study of the results reported by these and other investigators reveals a diversity of opinion as to the constancy of certain postmortem lesions in guinea pigs infected with *B. abortus* Bang, and suggests that if such postmortem examination is to be of any value in substantiating the results obtained by serologic and cultural methods, the following points may well be considered: (1) Does *B. abortus* Bang infection manifest itself by gross pathological changes in certain organs? (2) If so, are these changes constant enough to prove of any value as an aid in diagnosis? (3) Does the source of the abortion infected material have any influence upon the nature of the postmortem lesions? (4) Does the length of the period of inoculation influence the pathologic changes incident to the disease? It was in answer to these questions that our observations of the influence of abortion infection on the weight of the spleen of the guinea pig were instituted, as this organ in many instances gave gross evidence of pathologic involvment when infected with *B. abortus*.

The data recorded herewith represent our observations on the autopsy of 87 guinea pigs in five years of investigational work in bovine infectious abortion. Infection in these pigs has in each instance been proved by direct culture and serologic test. The material with which these pigs were infected represents a variety of sources—fetal and placental material, milk and colostrum, cultures, and miscellaneous. The guinea pigs used in our routine inoculation of various materials of which the 87 positively infected ones herein recorded represent only a small percentage, were taken from supply stock without special regard to either age, weight, or sex. All pigs used were those that had made normal growth gains and were in apparent health at the time of inoculation.

WEIGHING AND AUTOPSY TECHNIC

After inoculation, the procedure of which will be discussed in conjunction with a review of the various charts, the pigs were confined in cages and allowed to remain for a variable period, ranging from three weeks to two months depending upon the nature of the material injected. Before autopsy all food was withheld for a period of 12 to 15 hours in order that the influence of the ingesta on the body weight would be approximately the same in all individuals. The animals were carefully weighed and the weights recorded in grams. All pigs were anesthetized by chloroform in an enclosed chamber and killed by severing the jugular. During this operation the blood was collected in a sterile centrifuge tube corresponding in number to the pig from which it was obtained, and set aside at ice-box temperature to be tested later by means of the agglutination test for the presence of abortion infection. The carcasses were next stretched upon metal trays and the hair coat of the abdomen was moistened with 5% phenol preparatory for autopsy. The skin was incised along the median line from the pubis to the cariniform cartilage of the sternum, at which points transverse incisions were made extending well toward the extremities. Dissection of the skin from the lateral abdominal and thoracic walls and reflexion of the entire muscular wall of these two cavities exposed the organs for observation. The spleen was removed by severing the gastro-spleenic omentum with sterile scissors and forceps. After removal, the spleen was transferred to a sterile petri dish and the omentum was removed as close to the hilus as possible without injury to the spleenic tissue. As the presence of varying amounts of this omentum would necessarily influence the weight of the spleen, great care was always taken that it was completely removed. After completing the further autopsy, the spleen was weighed on an analytical balance and the weight recorded in grams to the third decimal. After obtaining the spleen weight, the substance of the organ was next cultured by direct transfer to serum agar. The following data were thus obtained:

1. Body weight in grams.
2. Spleen weight in milligrams.
3. Blood for serologic tests to check infection with *B. abortus* Bang.
4. Direct culture of the spleenic tissue further to check *B. abortus* Bang infection.

The data obtained in the autopsy of 87 positively infected guinea pigs showed that the body weights of these pigs ranged from 298 to 917 grams. It at once became obvious that before any deductions could be drawn on comparative weights of spleens, the normal weight of this organ must be determined for varying body weights.

DETERMINATION OF THE NORMAL WEIGHT OF SPLEENS

For the mathematical determination of the normal weight of guinea pig spleens based upon the body weight, we are indebted to the work of Bessesen and Carlson(5). These investigators, after an extended study of 82 guinea pig autopsies and a careful comparison of the relationship in the weight of certain organs and the body weight, were able to derive simple mathematical formulas to fit each growth curve. These formulas applied to the determination of the normal spleen weight were as follows:

$y=ax-b-cx^2$ For body weight of
$a=.0032 \quad b=0.08 \quad c=0.000005$ 100–300 grams

$y=ax+b+cx^2$ For body weight of
$a=0.00054 \quad b=0.205 \quad c=0.0000007$ 300–1000 grams

y=Spleen weight in grams.
x=Body weight in grams.
a, b, and c are constants.

A comparison of the above method of computation with the spleen weights of many non-infected guinea pigs used in our work has shown it to be reasonably accurate, altho there are instances in which there is considerable variation, as these formulas are based primarily on average observations. However, their relative accuracy can not be questioned.

Having the body weight, "x", by direct measurement, we were enabled by the use of the above formulas to compute the normal spleen weight in each case. We then had a basis for comparison of the effect of *B. abortus* infection upon the weight of spleens.

PRESENTATION OF DATA

In order that the statistical data obtained might be presented in concise form, graphs have been made. The charts are plotted with the spleen weight as the ordinate and the gross body weight as the abscissa, with the exception of Chart VIII, in which the number of days of inoculation represent the abscissa. To facilitate a direct comparison of infected spleens and norms, the normal curve based on the gross body weight was plotted on each chart.

OBSERVATIONS

CHART I

Chart I is the graphic presentation of the variation in weight of the spleens of 87 guinea pigs infected with *B. abortus* Bang, without regard to source of material or number of days of inoculation. These weights range from 4.627 to 0.530 grams. In five individuals, or 5.7%, the weight of the infected spleens is below that of the computed norm. It is possible that the actual weight obtained in these instances represents the norm for these individuals, as none of them presents any marked difference from the computed norm curve.

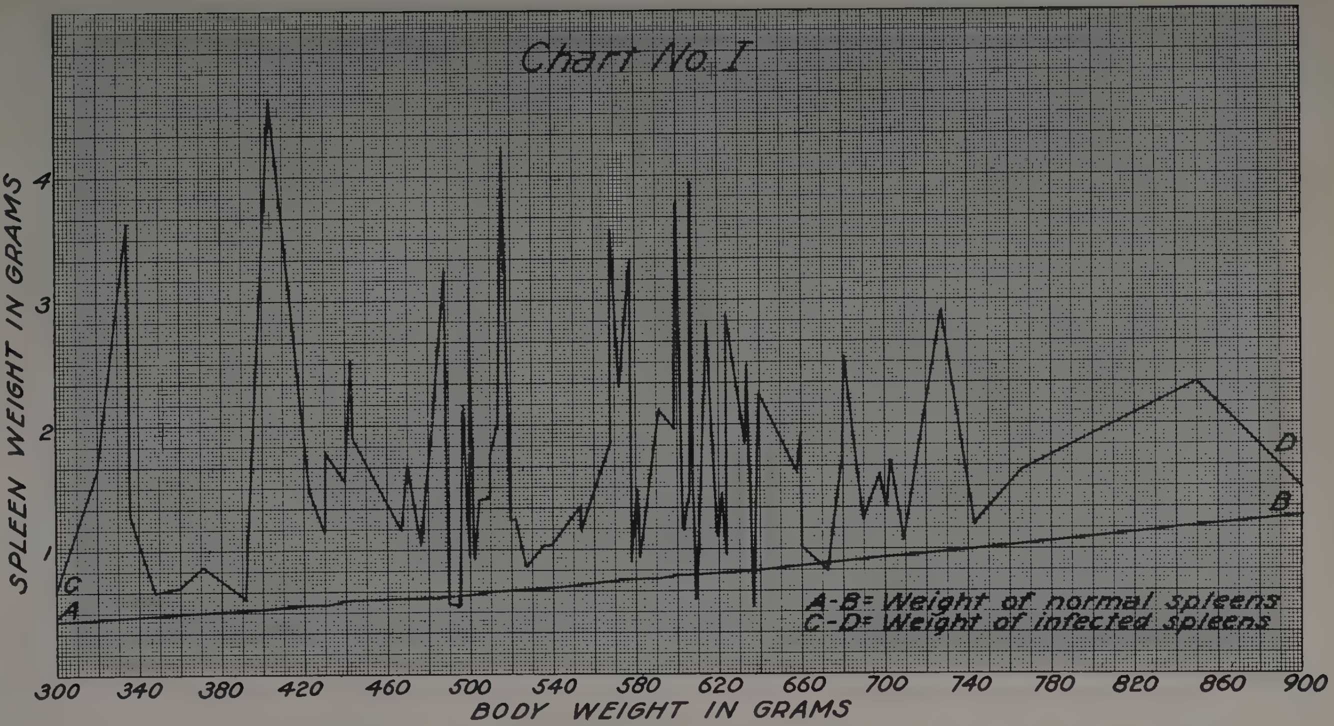
Chart No I
SPLEEN WEIGHT IN GRAMS
1
2
3
4
BODY WEIGHT IN GRAMS
300
340
380
420
460
500
540
580
620
660
700
740
780
820
860
900
A
B
C
D
A-B= Weight of normal spleens
C-D= Weight of infected spleens

CHART II

Chart II represents the data of Chart I with the values plotted in the form of a mean curve. We find here that the average weight of all infected spleens is substantially above that of the norm curve, being 1.695 as compared to 0.734 grams for the norms.

These averages show that the weight of the spleen is materially increased in guinea pigs infected with *B. abortus* Bang. However, after a study of Chart I, the data of which present such a wide variation in weight of spleens, the following questions present themselves: (1) Does the source of the organism and possible virulence have any bearing upon the weight of the spleen? (2) Does the change in weight of the spleen bear any relation to the number of days of inoculation? Graphs were constructed on the basis of material injected and the number of days of inoculation in an effort to answer these questions.

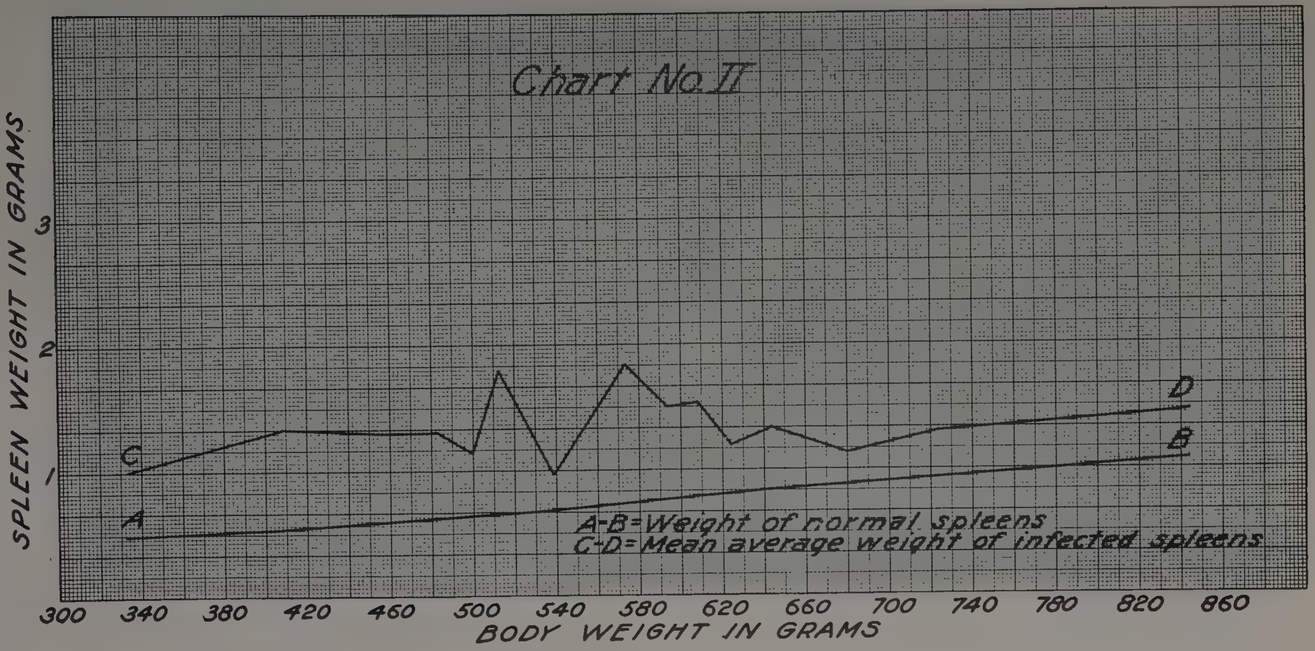
Chart No II
A-B=Weight of normal spleens
C-D=Mean average weight of infected spleens
A
B
C
D
SPLEEN WEIGHT IN GRAMS
1
2
3
BODY WEIGHT IN GRAMS
300
340
380
420
460
500
540
580
620
660
700
740
780
820
860

CHART III. FETAL MATERIAL

The inoculated material represented in this group consisted largely of fetal stomach contents. In the routine autopsy of feti, ligatures were placed at the esophageal and pyloric orifices of the stomach. After removal, a portion of the stomach wall was seared by means of a hot spatula and incised with a sterile sharp-pointed bistoury. The stomach contents were collected in a sterile container. When considerable amounts of mucous were present, it became necessary to dilute the material with physiologic saline solution before injection. The average amount of material injected ranged from 1½ to 3 cc., given intraperitoneally.

Thirteen guinea pigs having an average weight of 576.4 grams were injected with the above material. The average number of days of inoculation for the group was 42.5. An analysis of the data of Chart III shows that material from the same general source gives rise to a variation in spleen weight ranging from 4.627 to 0.572 grams, with an average of 2.241 grams for the group. The spleenic norm of the 13 pigs used, computed on the basis of average body weight, is equal to 0.738 grams. We find therefore that the average weight of infected spleens in this group has been increased approximately three times that of the normal.

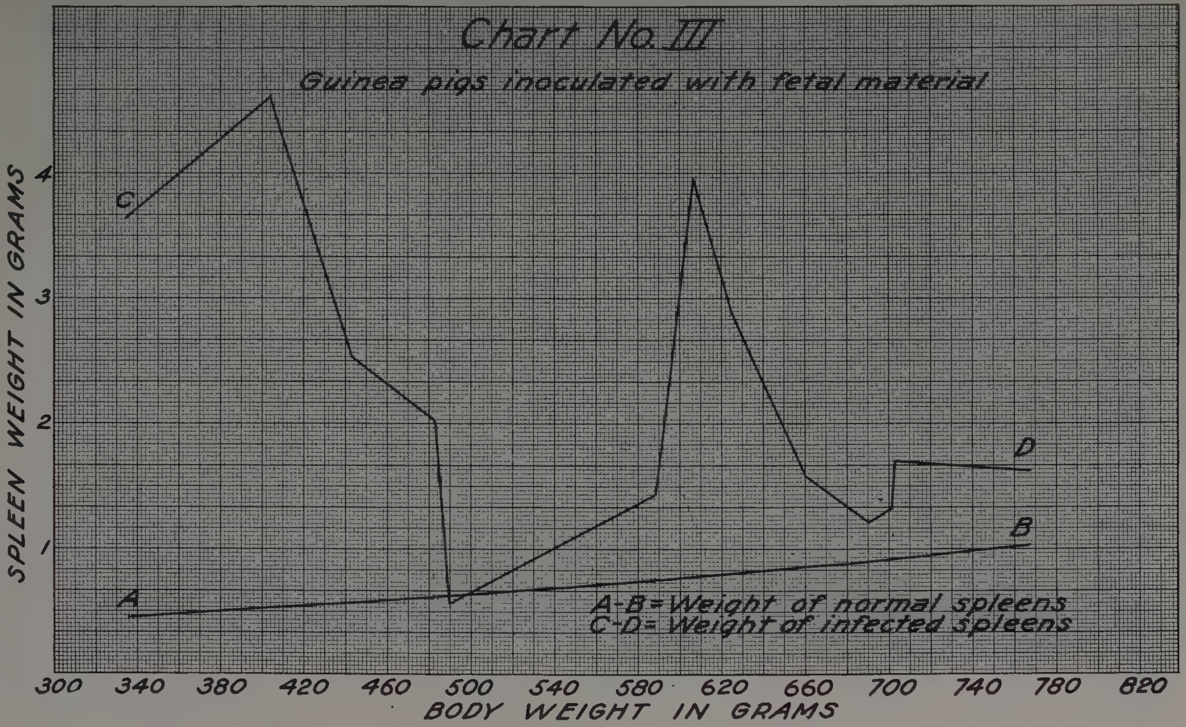
Chart No. III
Guinea pigs inoculated with fetal material
C
D
A
B
A-B = Weight of normal spleens
C-D = Weight of infected spleens
SPLEEN WEIGHT IN GRAMS
1
2
3
4
300
340
380
420
460
500
540
580
620
660
700
740
780
820
BODY WEIGHT IN GRAMS

CHART IV. PLACENTAL MATERIAL

Immediately upon the removal of placental tissue, the chorion was examined and portions of the numerous tufts showing gross evidence of pathological change were removed. The material thus obtained was placed in a sterile mortar and thoroly triturated with the addition of physiologic saline. From ½ to 1 cc. of this saline suspension of placental tissue was injected intra-peritoneally.

Nine guinea pigs having an average body weight of 550.6 grams were infected by this means. The average period of inoculation for this group was 43 days.

It will be observed that the weights of infected spleens in this group with one exception range between 1 and 2 grams with an average of 1.776 grams, while the norm computed on the basis of the average body weight for the group of nine is 0.7237 grams. This increase is found to be somewhat less than that shown in Chart III.

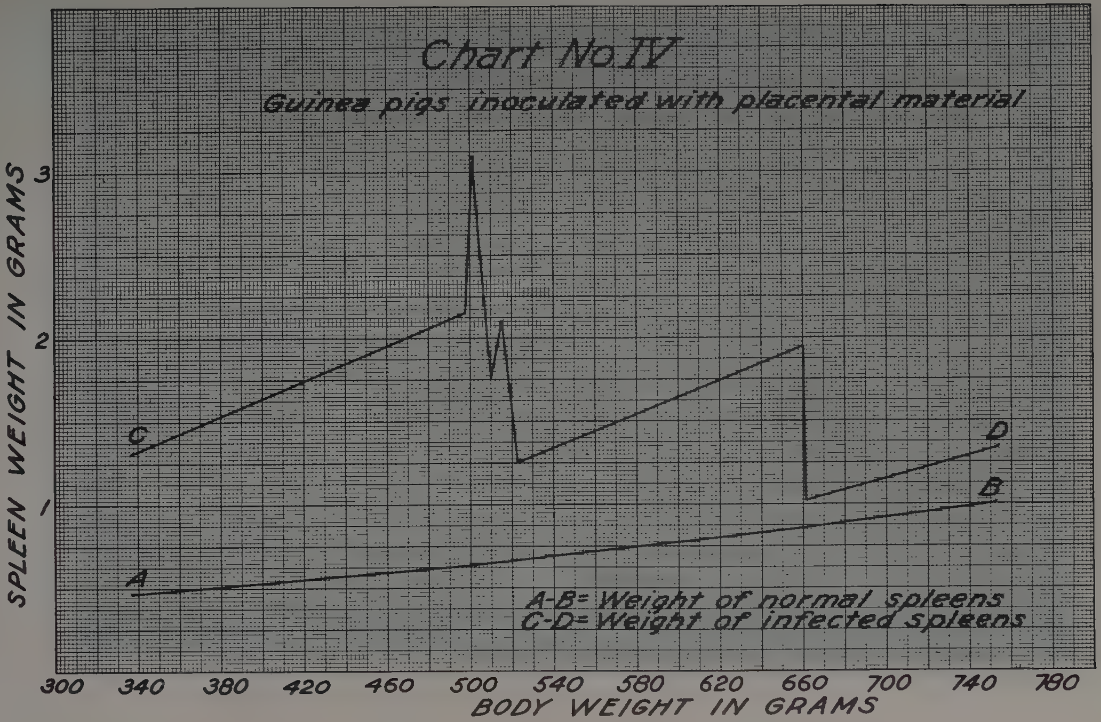

Chart No IV

Guinea pigs inoculated with placental material

CHART V. MILK AND COLOSTRUM

It has been our practice in studies in infectious abortion to make routine guinea pig inoculations with colostrum and milk from animals known to be infected with the Bang germ in order to determine its presence in these fluids. For this purpose approximately 1000 cc. of milk is obtained in a sterile flask from the four quarters of the udder and transferred to a sterile separatory funnel, where it is allowed to remain for 18 to 24 hours. At the end of this period samples of the milk are drawn into two 100-cc. centrifuge tubes and centrifuged for one and one half hours. The supernatant fluid is then removed and the sediment injected into a guinea pig, the amount ranging from 3 to 5 cc. At the same time a 5-cc. sample of whole non-centrifuged milk from the same cow is injected into a second pig. All inoculations are made intra-peritoneally.

The data of Chart V represent 39 infected guinea pigs of an average weight of 548.5 grams. The average period of inoculation was 42.2 days. While there appears to be a rather wide range in the weight of infected spleens, yet we find that only 7 of the entire 39 spleens show a weight exceeding 2 grams with an average of 1.492 grams for the group. The computed norm spleen weight based on the average for the group is 0.7340 grams.

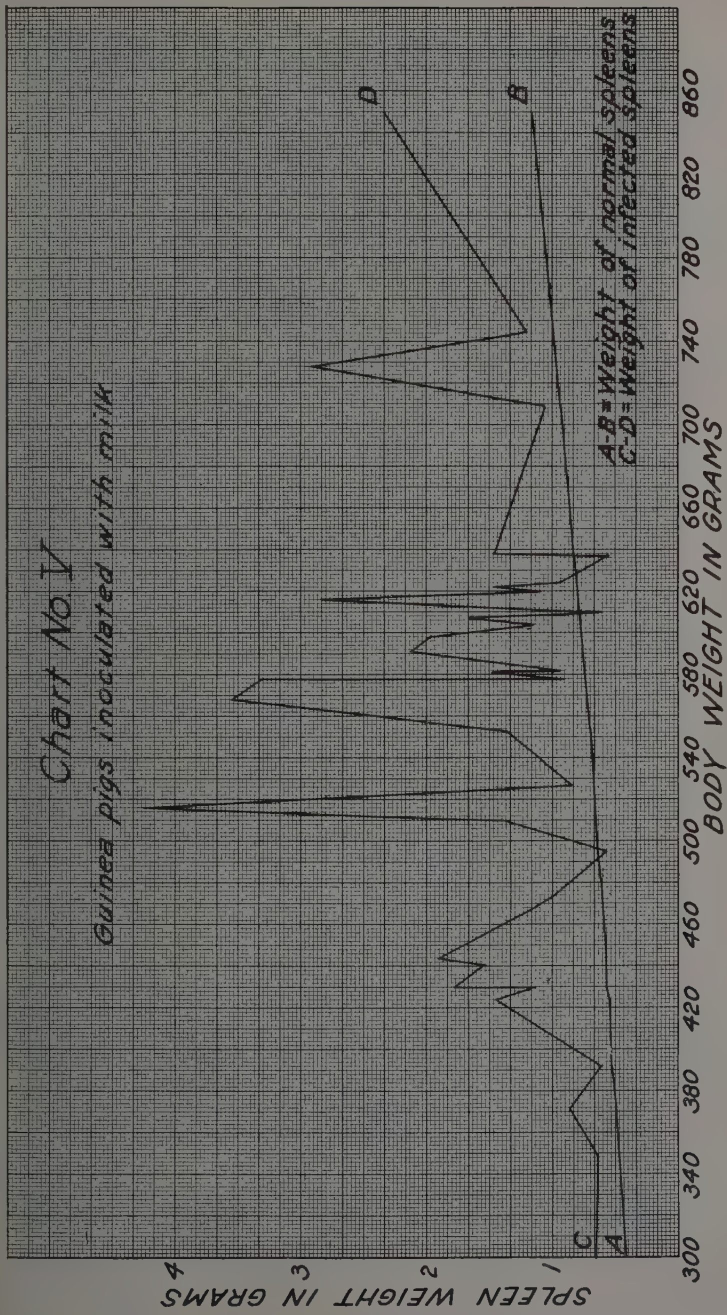
Chart No. V
Guinea pigs inoculated with milk
A-B = Weight of normal spleens
C-D = Weight of infected spleens
A
B
C
D
BODY WEIGHT IN GRAMS
300
340
380
420
460
500
540
580
620
660
700
740
780
820
860
SPLEEN WEIGHT IN GRAMS
1
2
3
4

CHART VI. *B. ABORTUS* CULTURES

The infective material of Chart VI is represented in part by cultures which were obtained from suspected abortion infected material and passed through guinea pigs for purposes of isolation of the Bang organism; also by stock abortion cultures for purposes of study of various properties.

Seventeen guinea pigs having an average weight of 547 grams were infected by this means. The average period of inoculation was 43.7 days.

As may be expected when the nature of the infective material and the varying amounts injected are considered, the infected spleen weights vary to a considerable degree, namely from 0.564 to 3.788 grams, with an average of 1.815 grams. The average norm spleen weight for the group is 0.7093 grams.

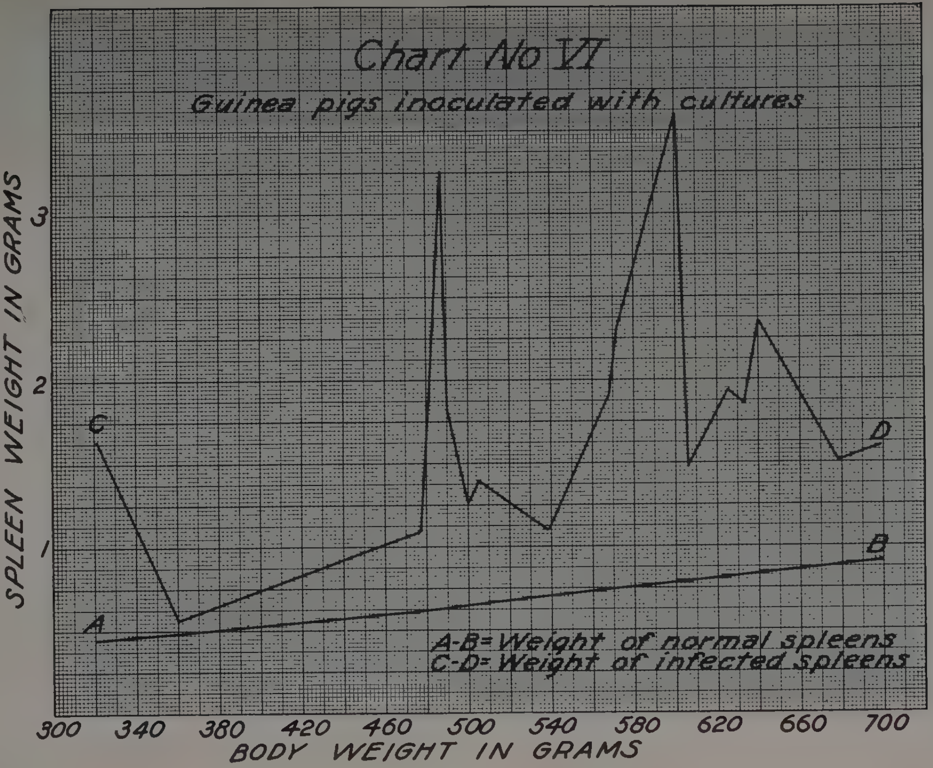
Chart No VII
Guinea pigs inoculated with cultures
SPLEEN WEIGHT IN GRAMS
3
2
1
C
D
A
B
A-B= Weight of normal spleens
C-D= Weight of infected spleens
300
340
380
420
460
500
540
580
620
660
700
BODY WEIGHT IN GRAMS

CHART VII. MISCELLANEOUS

Infective substances represented in Chart VIII are made up of miscellaneous materials encountered in our routine examination of suspected abortion in diagnosis work and not included in the graphs previously considered.

The abscess material was obtained from cases in which living abortion cultures had been used for vaccination purposes, and in which it was found necessary to drain the abscesses which sometimes resulted from this procedure. It may be observed that of the 9 guinea pigs infected with miscellaneous material, the 3 inoculated with abscess material show much higher spleenic weights than the others. This may possibly be explained on the basis of virulence of the organism. With the exception of that of one pig injected with vaginal discharge, the remaining 5 spleens show very little variation in weight.

The average weight of the 9 spleens represented is 1.505 grams, as compared with the computed norm of 0.7378 grams based on an average body of weight of 568.2 grams. The average period of inoculation for the group was 35 days.

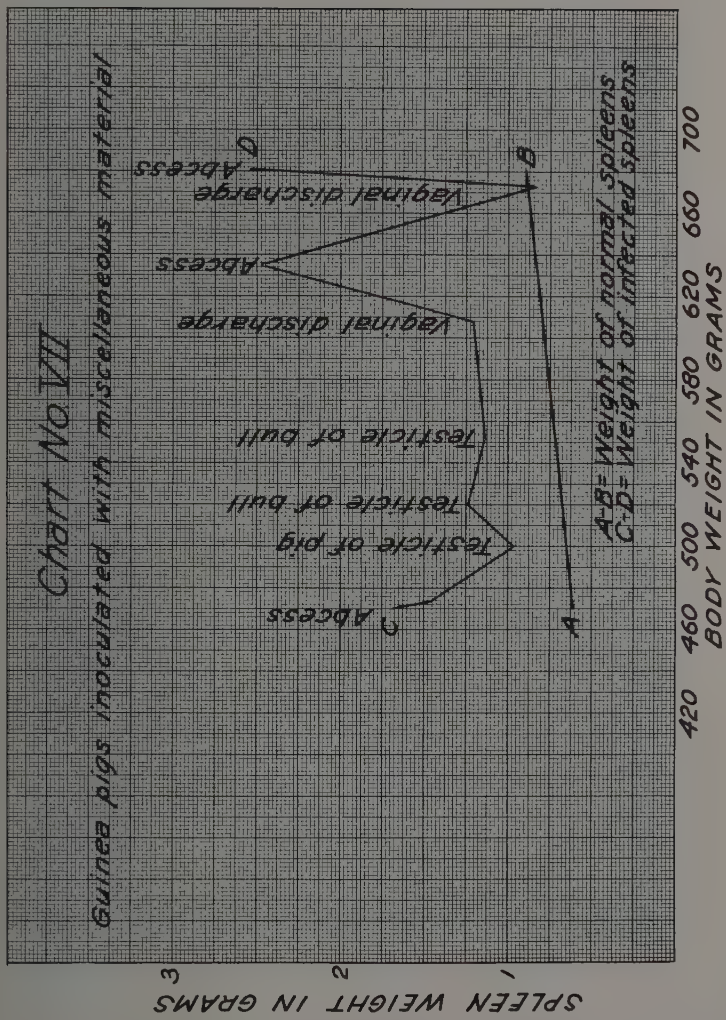

Chart No VII

Guinea pigs inoculated with miscellaneous material

CHART VIII. PERIOD OF INOCULATION

Chart VIII was prepared in order to determine the effect of the duration of time following inoculation on the weight of spleen. This graph was constructed with the abscissa representing the number of days of inoculation, and the ordinate, the spleen weight. The normal spleen weight was computed on the average body weight of the pigs inoculated for a definite period. For example, 3 pigs having an average body weight of 454 grams with a computed spleen norm of 0.5944 grams, and an average infected spleen weight of 3.069 grams were inoculated for a period of 28 days. No effort was made to classify the infected animals on a basis of materials used, as this phase of the question had already been considered. From the above example it will be noted that as the graph values represent the averages of different numbers of individuals, such values are only comparable to a relative degree, and in a sense are proportional to the number of animals considered. If the extremes as represented were to be eliminated when only one or two were considered per given period, the values would be regular in character and fall within comparatively narrow limits. After considering these various factors, we may conclude with a fair degree of accuracy that after 24 days (the minimum represented) the length of the period of inoculation is not proportional to and does not materially affect the spleenic weight.

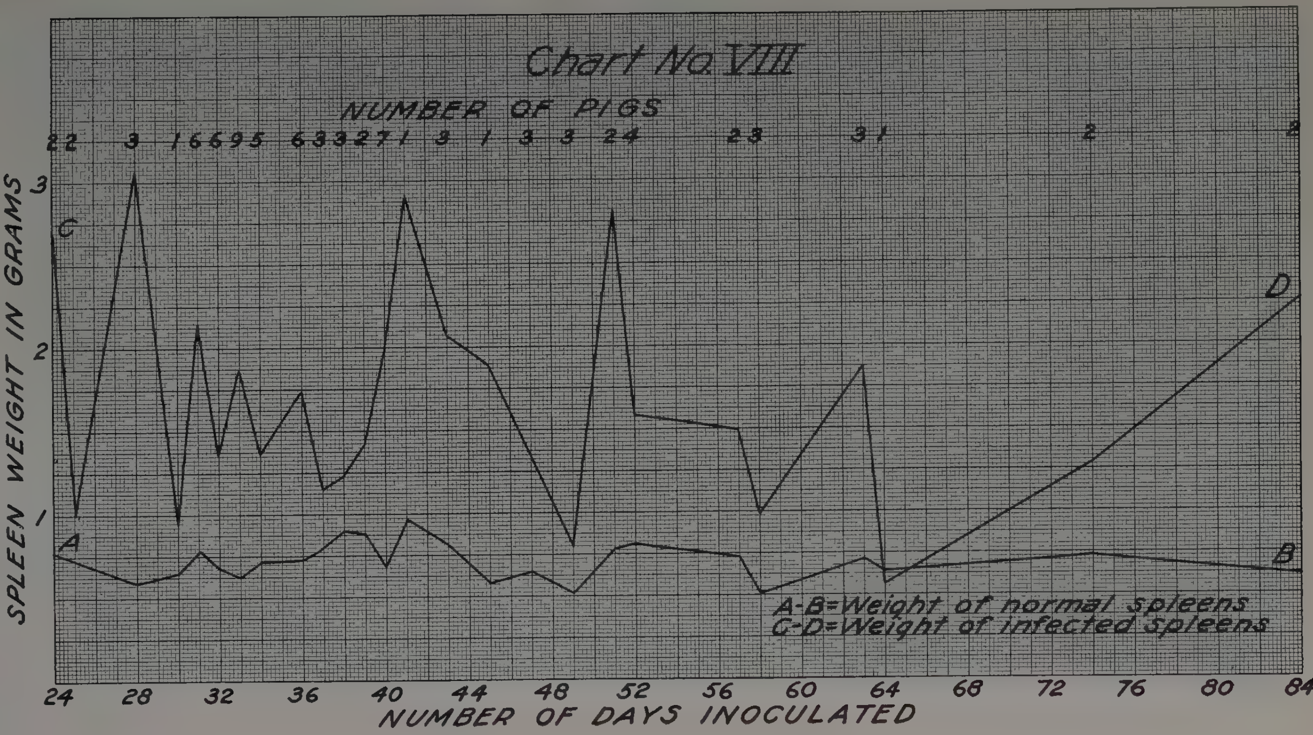

Chart No. VIII

SUMMARY

In order that the data obtained from our observations on the influence of various abortion infected materials may be compared, the following table is presented:

Material	No. of pigs inoculated	Av. weight of pigs	Av. norm. spleen weight	Av. infected spleen weight	Av. No. of days of inoculation
Fetal	13	576.4	0.7488	2.241	42.5
Placenta	9	550.6	0.7145	1.776	43.0
Milk	39	548.5	0.7117	1.492	42.2
Cultures	17	547.0	0.7108	1.815	43.7
Miscellaneous	9	568.2	0.7378	1.505	35.0
	87	558.8	0.7247	1.695	41.3

We find that the average body weight and consequently the computed spleenic norm of the guinea pigs used for each group are not variable to any extent and therefore compare quite closely to the average for the entire 87 pigs. Again it will be observed that with the exception of the miscellaneous group the length of the period of inoculation is very nearly equal, and even if we include the miscellaneous group, the average thus obtained does not differ materially from that of any one group. Therefore as the weights of the pigs, spleenic norms, and length of period of inoculation compare very closely in these various groups, we are justified in making a direct comparison of the infected spleen weights, as these represent the average of each group.

While these observations indicate that there is an increase in the spleen weight of pigs infected with *B. abortus* Bang, yet considering that various other factors may give rise to spleenomeglia, such an increase alone can not be considered of diagnostic value without the actual demonstration of the organism. While it is true that in spleenomeglia due to abortion infection there are gross and microscopic pathologic changes that are quite characteristic, it is likewise true that *B. abortus* Bang may be recovered from spleens showing little or no gross change. It is because of these exceptions to the average that we can not place too much reliance upon the use of the spleen weight as an aid in the diagnosis of *B. abortus* Bang infection.

CONCLUSIONS

1. *B. abortus* Bang infection in guinea pigs may and usually does give rise to a marked increase in spleen weight.

2. Infective materials from various sources seem to affect the spleen weight in varying degrees.

3. After the first 24 days (minimum considered) the length of the period of inoculation bears no relation to the increase in the weight of the spleen.

4. *B. abortus* Bang may be isolated from spleens which show no increase in weight or gross evidence of pathological involvement.

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TECHNICAL BULLETIN 25 DECEMBER 1924

The University of Minnesota
Department of Agriculture

Potato Breeding Methods

F. A. Krantz
Division of Horticulture

UNIVERSITY FARM, ST. PAUL

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Potato Breeding Methods

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POTATO BREEDING METHODS

By Fred A. Krantz

INTRODUCTION

The first improvement of the Irish potato (*Solanum tuberosum*, Linn.) probably occurred in prehistoric times. When the Spaniards invaded Peru in 1524 they found that the potato was a common article of food among the Indians, and that its cultivation was general over that region. The Incas of Peru had developed innumerable varieties which were adapted to the varying soil and climatic conditions of that mountainous country. Potatoes were introduced into Europe in the latter part of the sixteenth century. They came into general cultivation in Europe and North America about two hundred years later. It was not, however, until the beginning of the last half of the nineteenth century that progress was made in either Europe or North America, in producing varieties better adapted to the different soil and climatic conditions. In the forty-year period between 1850 and 1890 notable improvement in potato varieties was made in America. Our standard commercial varieties of today were originated during this period. Since 1890, with the exception of the russet types of the Burbank and Rural varieties, whose occurrence was fortuitous and whose origin is obscure, little progress has been made in obtaining better varieties. The absence of progress has not been due to lack of effort, altho since 1890 emphasis has been placed on clonal selection instead of on the sexual breeding method which was practiced during the previous forty-year period. Improvement of varieties in Europe was contemporaneous with their improvement in this country. In Europe, however, considerable progress has been made in recent years in the production of better varieties. It is of interest to note in this connection that the European breeders have never abandoned the sexual method of potato breeding. The importance of the potato crop in this country precludes the thought that the defects of the present standard commercial varieties will always be allowed to exist. It is therefore advisable to make a careful scrutiny of the different methods practiced in potato breeding for the purpose of a determination of their relative value to the plant breeder in the production of improved varieties.

The methods employed to secure improved varieties of potatoes may be conveniently divided into (1) clonal selection and (2) sexual breeding. These two methods are fundamentally different. The various modes of attack within these two methods will be discussed under separate headings.

The writer is indebted to W. H. Alderman and H. K. Hayes for their encouragement of the potato breeding work, and for the many constructive criticisms and suggestions made during the progress of this study.

CLONAL SELECTION

PURE LINE THEORY

Johannsen (18) considered a pure line to be the progeny of one or more self-fertilizations from a single homozygous ancestor. The pure-line theory has been extended to cover clonal or asexual propagation in both plants and animals. Johannsen worked with self-fertilized crops and found that selection within such a pure line was of no practical value. Similar investigations by Früwirth (10), Hutcheson (17), Hayes (13), and Love and Craig (26), with self-fertilized crops have been made and corroborate the results of Johannsen. While variations occur within such pure lines, these variations are found not to be inherited.

Investigations on asexually propagated plants have been numerous, but owing probably to the nature of the material they have not been so conclusive as those with self-fertilized crops. For a review of the literature on clonal selection previous to 1916 see Dorsey (3). The evidence here presented indicates that in the potato and in the deciduous fruits the asexual progeny of a single original heterozygous individual may be considered as a pure line. This conclusion is further supported by the more recent work of Crandall (2) on the apple. In certain other vegetatively propagated plants, selection appears to be necessary in order to maintain the parental type. Stout (46), working with coleus, was able to isolate types differing from the parent plant in foliage coloration and in form of leaves. It is interesting to note that in coleus, Stout considers "several of the principal types" to have arisen by "fluctuating variations." Shamel and co-workers (37, 38, 39, 40) have presented evidence purporting to show that selection in citrus is a practical method for improvement. Recently Sax and Gowen (36) have questioned the interpretation placed on these results in the light of the variability which they found that was due to known environmental causes. Isolated cases of mutations in pure lines derived from self-fertilized crops have been reported, but such mutations are too infrequent to be depended upon for a determinate system of breeding. In vegetatively propagated plants the importance of mutations in the production of new types appears to be dependent on the material. Mutations in the potato clone have been reported, but the results of investigation reported by East (4, 7, 8) and Krantz (21) indicates that the stability of the potato under asexual propagation approaches that of a pure line derived from self-fertilized crops.

RESULTS OF PRACTICAL INVESTIGATIONS

Very few of the many experiments are of any value in determining whether new genotypes arising through mutations are sufficiently numerous to justify selection in the clone as a means of isolating them. Despite the fact that East (6) in 1910 called attention to the influences which tended to obscure the results of earlier investigators and pointed out that proper conclusions can be drawn only after controlled experiments upon an accurately measured character by the use of biometrical methods, the investigations since 1910 can hardly be said to show much improvement. For a review of the literature on clonal selection in the potato, the reader is referred to East (6) in 1910, Stuart (48) in 1915, and Krantz (21) in 1923. Progenies from both individual tubers and individual hills differing in productivity have been isolated. The explanation of this is clear when considered in the light of our present knowledge concerning degeneration diseases. It is significant that in spite of the many experiments reported on clonal selection in the potato, no types have been isolated yielding above the optimum of healthy seed stock of the variety. A few experiments have been reported on characters other than yield. Stewart (45) and Wellington (53) were unsuccessful in isolating types resistant to the degeneration diseases. White (55) was unable to isolate a different form of the white McCormick variety.

PRELIMINARY WORK ON CLONAL SELECTION

Kohler, in 1913, made a comparison of the progenies secured from planting round and long tubers of four seed stocks. The results, given in Table I, are taken from his unpublished data.

TABLE I

FORM OF TUBER OBTAINED FROM PLANTING ROUND AND LONG TUBERS OF THREE VARIETIES

Plot	Variety	Shape of tubers selected	Mean ratio of width to length of tubers in progeny	Number of tubers measured
1	Early Ohio	round	1:00: 1.30 ± .01	166
		long	1:00: 1.31 ± .01	129
2	Green Mountain	round	1.00: 1.24 ± .02	97
		long	1.00: 1.24 ± .02	60
3	Rural New Yorker	round	1.00: 1.30 ± .01	452
		long	1.00: 1.29 ± .01	277
4	Rural New Yorker	round	1.00: 1.33 ± .01	302
		long	1.00: 1.33 ± .01	274

In Table I are given the plot numbers, the varieties studied, the shape of the tubers selected, the mean ratio of width to length of tubers in the progeny, and the number of tubers measured in each determination. As the progeny of each tuber was not kept separate, the results do not preclude the presence of different biotypes for form of tubers in the varieties. They show that the differences in form observed in the parental stock were not due to the presence of different genotypes. Whether types exist within the variety which have arisen through mutation can be determined only by a systematic attempt to isolate them. Either mass selection of extremes over a period of time or individual tuber unit and hill selection would have to be undertaken to determine this point. In 1914, Wellington began extensive tuber tuber unit and hill selection studies but found the method to be impractical owing to the presence of degeneration diseases. In 1916, Wellington and Aamodt began a study based on mass selection. The basis of this study consisted in the fact that two growers had practiced mass selection in the Early Ohio variety for twenty years and had achieved what they considered improvements in yield and type. It was thought that a comparison of these two seed stocks with other seed representing distinct different regional types, would throw some light on the presence of biotypes within varieties and would also ascertain the practical value of clonal selection. As a large part of this study has been presented in a previous paper by the writer [Krantz (21)] only the summarized results will be given.

EFFECT OF SELECTION FOR INCREASED YIELD

Seed stocks from seven growers were used in this study. Six of these (Nos. 2, 3, 4, 6, 7, and 8) were obtained in the fall of 1916. The seventh (No. 9) was obtained in the spring of 1920. The seed stocks obtained in 1916 were tested for yield for four years at four different places in Minnesota, namely, University Farm, Duluth, Grand Rapids, and Crookston[1]. Seed stock No. 9 was given a yield test in 1920.

The "Student method" (52) was used to determine the significance of the differences in yield obtained between the various seed stocks. The method is illustrated by a comparison of Nos. 2 and 7.

The odds are 3.6 to 1 that the difference in yield between 2 and 7 is significant. In Table II the odds in favor of a significant difference between any two lots is given.

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[1] Thanks are due to O. I. Bergh, M. J. Thompson, and T. M. McCall for their co-operation at the substations.

Yields of seed stock No. 2	Yields of seed stock No. 7	D	D^1	D_1^2
205	261	−56	66.7	4,448.89
203	202	1	9.7	94.09
326	316	10	0.7	0.49
44	71	−27	37.7	1,421.29
255	248	7	3.7	13.69
158	156	2	8.7	75.69
286	297	−11	21.7	470.89
206	197	9	1.7	2.89
245	197	48	37.3	1,391.29
323	208	115	104.3	10,816.00
150	130	20	9.3	86.49
		M=10.7		11)18,821.70 1,711.06

$\sqrt{1,711.06}=41.36$

$\frac{M.}{S.D.}=Z=\frac{10.7}{41.36}=0.26$

P=0.7822 Odds=3.6 : 1

TABLE II

Significance of Difference in Productivity Between Seed Stocks as Indicated by the Odds Obtained

Seed stock	3	4	6	7	8
2*	1:1	3:1	6:1	4:1	2:1
3		2:1	11:1	3:1	1:1
4			7:1	1:1	2:1
6				14:1	18:1
7					3:1

* Selected for twenty years.

The odds given show that there was no significant difference between the productivity of No. 2 and the other seed stocks. Mass selection for twenty years by the grower had failed to isolate a higher yielding strain. The greatest odds that there is a significant difference in yielding ability was obtained in the comparison of Nos. 6 and 8, both of which were unselected lots. If all the six seed stocks were of equal inherent productivity value, a difference as great as this could be expected to occur through chance alone in one out of three similar tests. Seed stock No. 9 was tested one year in comparison with Nos. 2 and 7. It gave an intermediate yield between them.

VARIABILITY BETWEEN SEED STOCKS OF A VARIETY

Difference in yield between seed obtained from different growers of a variety have been pointed out by Macoun (27), Stuart (50), Rosa (30), Werner (54), Hardenburg (11), Moore (28), and other investigators. Stuart (51), in a recent paper, states: "Careful comparisons of many strains by many observers in different localities and under different climatic conditions have demonstrated beyond any possiblity of refutation that certain strains are very much heavier yielders than are others of apparently equal merit as far as outward appearances are concerned." A theoretical basis for this belief is difficult to find. If mutations influencing productivity of seed stocks do occur, there is no reason for supposing that they occur more frequently in the seed stocks of some growers than in those of others, as they would always result in better yields or improved tubers.

A few seedlings have been introduced into the trade which have not been sufficiently distinct in their characters to exist as separate varieties and have been merged under one varietal or group name. If such introductions were numerous it would offer hope that seed stocks of a variety from different growers might be enough different in yielding ability to justify an attempt to isolate the highest yielding. The history of potato improvement in this country seems to indicate that such introductions have been relatively few in number.

It is not necessary to assume inherent differences in order to explain the cause of the differences obtained. In none of the tests reported have the factors of storage of tubers, disease, and soil heterogeneity been carefully evaluated. While the later investigations have recognized the importance of disease as a factor influencing the results, and have appreciated the necessity of similar storage conditions for the various seed stocks to be tested, the factor of soil heterogeneity has received little attention. The coefficient of variability of a series of tests in which a single seed stock was used will be compared with a series of tests in which each test represented seed stock of a different grower. Each test consisted of three systematically distributed two-rod rows. The results obtained are given in Table III. They illustrate the importance that soil heterogeneity plays in influencing differences in yield.

TABLE III

Comparison of Variability Obtained in a Single Grower's Seed Stock with the Variability Between Numerous Seed Stocks of the Early Ohio Variety

Year	Seed used	No. of tests	C. V.
1921	Single seed stock	40	11.3±0.85
1922	84 seed stocks	84	12.7±0.66
1923	Single seed stock	112	10.0±0.45

The amount of variability within a single stock was slightly less than within the variety, as judged by 84 random seed stocks obtained of the variety. The difference in the light of the probable error is not materially significant. It is also manifestly impossible to secure 84 seed lots from different growers that are as uniform for such a factor as disease as the condition within a single seed stock. All the seed was obtained from growers of certified potatoes through the courtesy of A. G. Tolaas, in charge of seed potato certification, and in regard to freedom from disease they were the best seed stocks of the variety obtainable. The lowest yielding lot yielded 170 bushels per acre and the highest 310 bushels, a difference of 140 bushels per acre. A similar amount of variability, however, was obtained between tests from a single seed lot, which indicates that soil variability was the cause of the difference in yield obtained. Such variation in yields due to soil heterogeneity may normally be expected, as has been pointed out by Harris (12). A comparison of the amount of variability due to soil heterogeneity in these plots with that obtained by Myers and Perry (29) is of interest.

TABLE IV

COMPARISON OF VARIABILITY IN POTATO YIELDS DUE TO SOIL HETEROGENEITY IN ONE PLOT AT THE CORNELL EXPERIMENT STATION AND TWO PLOTS AT THE MINNESOTA EXPERIMENT STATION

Cornell experiment station (After Myers and Perry)			Minnesota experiment station, 1921			Minnesota experiment station, 1922		
Size of plot	No. of tests	Coefficient of variability	Size of plot	No. of tests	Coefficient of variability	Size of plot	No. of tests	Coefficient of variability
Hills			Hills			Hills		
25	500	21.7 ± .344	22	120	20.2 ± 0.87	22	392	18.2 ± 0.43
50	250	17.7 ± .389	44	40	13.7 ± 1.06	44	176	17.2 ± 0.62
100	125	14.4 ± .443	88	...	....	88	88	14.9 ± 0.79

The coefficients of variability obtained for the different sized plots shows that the amount of variability due to soil heterogeneity was very similar in the three experiments, and it is probably what may ordinarily be expected on plots which appear uniform for experimental purposes.

The results of the study on productivity of the seed stocks lead to the conclusion that selection for twenty years by two growers has had no demonstrable effect in increasing the yield of these two stocks above the normal yield of the variety as judged by the yield of seed from five other growers. The results strongly suggest that there was no inherent difference in productivity among the seven lots. A study of 84 other seed lots of the Early Ohio variety indicates that there was no greater variability in productiveness between these than was obtained in similar tests with a single seed stock. Soil heterogeneity was apparently the greatest factor in causing variability in yield, and if differences in inherent productivity exist between seed stocks of this variety they are relatively very small. Comparative tests of certified seed potatoes are of value, however, as an aid to certification work, as they enable a critical study to be made of the various seed stocks in regard to the amount of disease present and the varietal purity.

SELECTION FOR TYPE OF TUBER

In the selection that was practiced by the two growers the emphasis was placed on type of tuber. Various tuber characters are concerned in the complex known as varietal type. An attempt at individual analysis of these was made for differences between the seed stocks.

Distinct differences existed between the original lots as regards form of tuber with the exception of Nos. 7 and 8, which were obtained from the same region. Each original lot was divided into four portions. A comparative test was made in 1917 at University Farm, Duluth, Grand Rapids, and Crookston. The form of the tubers produced at each of these places, as determined by observations, was similar in all the lots regardless of the original type. At each place the form of tubers was characteristic, and easily distinguishable from the types produced at the other places. In 1918, the progeny of each original lot grown was maintained separately, divided, and redistributed. The four portions of each original lot were brought together in a comparative test in 1918. At least two comparative tests between the four portions of each original lot were made with each of the seven original lots. This gave an opportunity to compare the four portions of each lot at two or more places and to determine if the four different growth conditions in 1917 affected in any way the crop of 1918. It also gave an opportunity to study further the progeny of the seven original lots for differences in type. The results were the same as in 1917. The tubers of all the lots were of the same form at each place, and bore no relation to the form exhibited the previous year. In 1919 and in later years, measurements were made of the tubers of the progeny of five of the original seed stocks and similar measurements were made of seed stock No. 9, which was obtained in the spring of 1920. In Table V are given the number of the seed stock; years and place grown; form as indicated by depth, width, and length stated in percentage of total dimensions; and the ratio of depth to width, depth to length, and width to length.

In 1919 the greatest differences were obtained at Duluth between Nos. 2 and 7. The form of tubers of these two lots when grown at Grand Rapids, however, was the same. The results obtained in 1920, when these two stocks were again grown at Grand Rapids, also supported the observations made in 1917 and 1918, and lead to the conclusion that inherent differences in form between these two lots did not exist. The form of tubers of the original seed lot, No. 9, which was obtained in the spring of 1920 from Hopkins, Minn., was distinctive. The tubers were long in relation to their depth and width, altho not abnormally so, the type being very good. The grower had practiced careful selection toward this type for twenty years. A test in comparison with three of the other seed stocks, in 1920 and 1921, showed that this seed lot was of the same inherent form as the others for it immediately assumed the same types as the other seed stocks with which it was grown in comparison. Both observations and measurements as given in the above table indicated this to be the case.

TABLE V

DATA OBTAINED ON TUBER FORM IN EARLY OHIO SEED STOCKS

Seed stock No.	Year grown	Place grown	No. of tubers	Shape in percentage of total dimensions			Shape ratios		
				Depth	Width	Length	$\frac{\text{Width}}{\text{Depth}}$	$\frac{\text{Length}}{\text{Depth}}$	$\frac{\text{Length}}{\text{Width}}$
2	1919	Grand Rapids	486	27.5	30.9	41.4	1.12	1.50	1.34
3	1919	“ “	80	27.1	30.4	42.5	1.15	1.59	1.40
6	1919	“ “	360	27.5	31.3	41.2	1.14	1.50	1.32
7	1919	“ “	126	27.6	30.8	41.4	1.12	1.50	1.34
8	1919	“ “	120	27.3	31.3	41.6	1.15	1.52	1.33
2	1919	Duluth	120	28.2	33.5	38.3	1.19	1.35	1.14
7	1919	“	120	27.8	32.1	40.1	1.15	1.45	1.25
9	1919	As obtained from grower	30	26.3	28.4	45.2	1.08	2.01	1.59
9	1920	Grand Rapids	80	27.9	31.5	40.6	1.13	1.46	1.29
2	1920	“ “	71	28.1	31.4	40.5	1.12	1.44	1.29
7	1920	“ “	63	27.5	31.1	41.4	1.17	1.51	1.33
2	1921	University Farm	247	28.3	31.9	39.7	1.13	1.40	1.25
9	1921	“ “	496	27.7	31.8	40.5	1.15	1.46	1.27
3	1921	“ “	210	27.8	32.3	39.9	1.17	1.43	1.24

It is of interest to note the sensitiveness of tuber shape to a change in environmental conditions, as is incidently brought out in Table V. A study of this table shows that at no two places was the same tuber shape obtained. It clearly illustrates that hereditary differences in tuber shape within the variety are negligible as compared to the diffences in expression of tuber form brought out by changes in growing conditions.

VARIABILITY IN TUBER FORM BETWEEN SEED STOCKS OF A VARIETY

Seed stocks as obtained from growers frequently present distinct differences in tuber form. A progeny test to determine the nature of these differences showed that they are non-heritable.

TABLE VI

Correlation of Tuber Shape of Original Seed Stocks as Obtained from Growers with Shape of Progeny When Grown in a Comparative Test at the Northwest Substation

Ratio of width to length of parent seed stocks	Ratio of width to length of progeny									
	1.36	1.40	1.44	1.48	1.52	1.56	1.60	1.64	1.68	Total
1.22		1			2					3
1.26		1			1	1			1	4
1.30			2		1		2			5
1.34				1	3					4
1.38	1		1			2				4
1.42		1		2	2					5
1.46					1		1			2
1.50					1					1
	1	3	3	3	11	3	3		1	28

r = −.004 ± .127

Ratio of depth to width of parent seed stock	Ratio of depth to width of progeny						
	1.06	1.08	1.10	1.12	1.14	1.16	Total
1.08		2					2
1.10	1		2				3
1.12	1	1	4	4	1		11
1.14	2	3	2	2		1	10
1.16		2	3				5
	4	8	11	6	1	1	31

r = −.049 ± .157

In Table VI the average tuber form of seed as obtained from different growers is correlated with the tuber form of the progeny. All lots were grown at the Northwest experiment station, Crookston, Minn. under similar conditions. The coefficient of correlation obtained between the parent stocks and their progeny when the average tuber ratio of width to length in each lot was used as an index of form was —.004±.127. When the average of depth to width was used as an index, the coefficient of correlation was —.049±.157. The coefficient of correlation is negative in both cases, tho mathemaically of no significance. The results show that the differences in tuber form between the seed as obtained from different growers was due to non-heritable factors.

The results of the five years' work show that the two growers who had practiced selection for twenty or more years had failed to isolate a form of tuber differing from the normal of the variety. It was further found that differences in tuber form between seed from different growers was not carried over to the progeny. The difference in form was evidently due to different growth conditions.

SELECTION FOR OTHER CHARACTERS

Observations were made on other tuber characters, in the original study of the seven early Ohio seed stocks, such as absence or presence of knobs and fissures, depth of eyes, prominence of eyebrows, color of tubers, and haulm characters. The study on these characters was similar to that made on form of tuber. While marked differences existed in the tuber characters between the original lots as obtained, they were not found to be hereditary differences. They were found to be expressed, unexpressed, or modified in their expression, depending upon the environmental conditions surrounding the development of the tubers.

In this study of variability in the Early Ohio variety, the evidence obtained points strongly to the conclusion that important hereditary differences are not occurring in the variety as a result of mutations. No evidence was obtained that would justify the practice of any of the methods of clonal selection other than as an aid to the control of diseases.

SEXUAL BREEDING

The origin of our present commercial varieties is of interest in determining the value of sexual breeding in the improvement of the potato. Stuart (48, 49) has collected the important facts available concerning their origin. As previously stated, the period in which most of the important potato varieties were produced was between 1850 and 1890. A few of the potato breeders during this period practiced hybridization. The most notable of these was Pringle. However, the large majority of the breeders grew seedlings from naturally set seed balls. The heterozygous condition of potato varieties led to sufficient variation in the seedlings to make this an encouraging line of work. These breeders introduced many promising seedlings into the trade.

Most of these seedlings have been eliminated in the struggle for commercial existence in the forty-year period since their introduction. Those seedlings that have survived constitute our present commercial varieties. Sexual breeding has given us our present commercial potato varieties and it is this kind of breeding rather than clonal selection that offers possibilities for further improvement.

A study of the possibilities of sexual breeding was made with material obtained during the progress of a potato breeding project which has been carried on at the Minnesota experiment station since 1921. Some breeding work carried on at the same station by Kohler from 1908 to 1913 furnished material which has aided in the progress of work. The studies of methods for securing improved varieties by sexual breeding will be discussed under the following headings: (1) Varietal crosses, (2) Selection within self-fertilized lines.

VARIETAL CROSSES

Most potato varieties produce insufficient viable pollen to make them dependable as pollen parents. Stuart (49) lists five varieties as dependable sources from which pollen may be obtained, namely, Early Silverskin, Irish Seedling, Keeper, McCormick, and Round Pink Eye. From the results of studies in pollen germination of 210 seedlings and miscellaneous varieties and from the records of several thousand crosses, Clark (1), Stout and Clark (47), concluded that McCormick, Busola, Keeper, and a few others were good pollen parents. Each of these varieties is inferior in many of its commercial characters to our present standard varieties. The varieties used as pollen parents in the study carried on in Minnesota are United States Department of Agriculture seedling 14329 (an F_1 seedling of Keeper × Early Silverskin), Lookout Mountain (McCormick group), and an unnamed variety from South America. The following standard varieties were used as female parents, Early Ohio, Cobbler, Triumph, Green Mountain, Burbank, and Rural New Yorker.

VIGOR OF F_1 SEEDLINGS

A study was made of the vigor of F_1 seedlings as compared to the vigor of seedlings of the self-pollinated parents. Owing to pollen sterility, seed was obtained from only four of the parents. The results are given in Table VII.

Four determinations were made of vigor. On July 2 height measurements were taken on each seedling. The average height of the seedlings in each row was then obtained. The results of the height measurements are given in column 1 of Table VII. On August 1, each row of the four series was given an arbitrary rating for vigor. The average rating for each progeny for the four series, with its probable error, was then obtained. The results are given in column 2. On September 10 each seedling was given an arbitrary rating for vigor. The data were then worked up by the same method as for the individual height measurements in the first determination. The results are given in column 3.

TABLE VII

COMPARISON OF F_1 SEEDLINGS WITH THE SELF-SEEDLINGS OF THEIR PARENTS

Name of parent or cross	1 Av. height of seedlings, July 2 (cm.)	2 Av. vigor of vine growth, Aug. 2	3 Av. vigor of vine growth, Sept. 10	4 Av. yield of seedlings, Sept.
Green Mountain	23.8 ± 1.0	6.0 ± 0.30	5.9 ± 0.40	4.7 ± 0.31
Green Mountain × U. S. D. A. seedling 14329	24.9 ± 1.0	8.5 ± 0.30	6.5 ± 0.40	6.1 ± 0.31
U. S. D. A. seedling 14329	19.9 ± 0.7	4.3 ± 0.20	4.8 ± 0.22	5.3 ± 0.19
Early Ohio × U. S. D. A. seedling 14329	24.2 ± 1.0	7.8 ± 0.30	5.8 ± 0.40	5.5 ± 0.31
Early Ohio	21.0 ± 0.6	7.2 ± 0.17	5.8 ± 0.22	5.2 ± 0.18
Rural New Yorker × U. S. D. A. seedling 14329	23.9 ± 1.0	6.5 ± 0.30	5.0 ± 0.40	4.7 ± 0.31
Burbank × U. S. D. A. seedling 14329	22.6 ± 1.0	5.7 ± 0.30	4.5 ± 0.40	4.3 ± 0.31
Triumph × U. S. D. A. seedling 14329	23.4 ± 1.0	6.0 ± 0.30	5.0 ± 0.40	4.2 ± 0.31
Cobbler × U. S. D. A. seedling 14329	24.9 ± 1.0	6.0 ± 0.30	6.1 ± 0.40	4.9 ± 0.31
Cobbler × Lookout Mountain	23.2 ± 1.0	8.7 ± 0.30	6.1 ± 0.40	5.0 ± 0.31
Lookout Mountain	16.6 ± 1.2	4.0 ± 0.35	5.4 ± 0.48	4.0 ± 0.38
Average of seedling of selfed parents	20.3	5.4	5.5	4.8
Average of F_1 seedlings	23.9	7.0	5.6	5.0

At time of harvest each seedling was rated for vigor on the amount of tubers it produced. The data on the individual seedlings were again compiled as in the first determination. The results are given in column 4. Four systematically distributed rows were grown of each progeny. The probable error was obtained by the "deviation from the mean yield" method. This method, presented by Hayes (15), is a modification of the pairing method presented by Wood and Stratton (59). By this method the separate varieties in the trials are used. The deviation from the mean yield of each variety is expressed in percentage and the formula applied, $S.D.=\sqrt{\frac{D^2}{N}}$. Hayes (15), compared the probable error obtained by this method ($P.E.=S.D.\times.6745$) with that obtained by the check plot method, pairing method (deviation not squared), and pairing method (deviation squared), with three crops, namely, wheat, oats, and barley, over a three-year period. He found that the probable error obtained by the "deviation from the mean yield" method approached the most closely that obtained by the check plot method.

To determine further the value of the "deviation from the mean yield" method in working with a crop like potatoes, it was compared with the check row method in a test consisting of 352 rows two rods in length. By the check row method of computation the standard deviation obtained was 33.8±0.9. By dividing the field into 88 units, each unit consisting of four systematically distributed two-rod rows, and applying the deviation of each of the four rows from the mean yield of the unit, a standard deviation of 32.3±0.9 was obtained. The results of this comparative test indicate that with potatoes the probable error obtained by the two methods will be of the same relative magnitude. That the method may justifiably be applied to the tests made with seedlings seems reasonable in the light of the results obtained by Hayes (15) in crops grown from seed. In both methods it is assumed that the variability is reduced through replications according to mathematical expectation. That the actual reduction in variability obtained through replication agrees with the theoretical reduction expected, has been shown by many investigators in farm crops as reported by the committee of Standardization of Field Experiments of the American Society of Agronomy (25, 56, 57, 58). In potatoes the writer [Krantz (23, 24)] and Salaman (34) have shown that the actual reduction in variability obtained through replication of rows agrees with the amount theoretically expected. A graphic illustration of the results obtained at Minnesota in 1923 is given in Figure 1. The two curves are in close agreement up to as high as 16 replications.

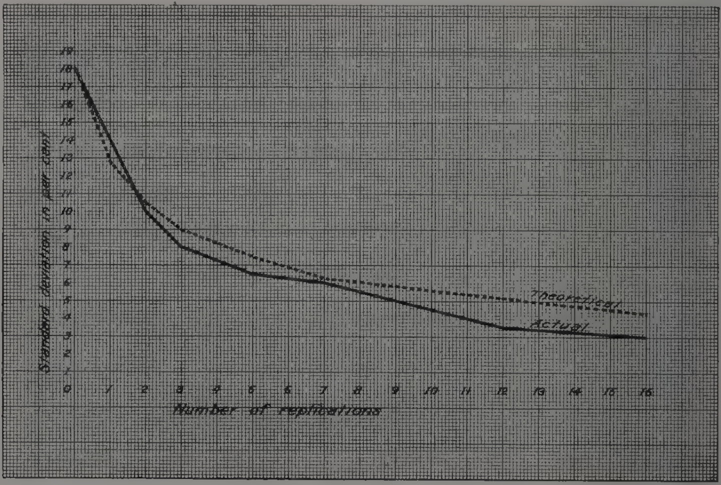

Fig. 1. Comparison of Actual Reduction in Variability of Yields Obtained Through Replication, with the Reduction Theoretically Expected

A study of Table VII shows that the F_1 seedlings were slightly more vigorous than the seedlings obtained from the selfed seed of their parents. In two of the crosses, Green Mountain × U. S. D. A. Seedling 14329 and Early Ohio × U. S. D. A. Seedling 14329, seedlings were grown from both parents. In both instances the F_1 seedlings were more vigorous than the seedlings from either parent, as determined by growth of vine and yield of tubers. It is interesting to note that the increased vigor was apparent at a very early stage in the growth of the seedlings. Differences in rate of growth were noted while the seedlings were in the greenhouse previous to transplanting.

The utilization of F_1 populations to secure improved varieties is limited, owing to the lack of pollen parents which have desirable commercial characters. The undesirable dominant characters of the parents, together with the undesirable recessives which are frequently hidden in the parents, make it difficult to obtain a seedling in the F_1 which has the desired commercial characters.

SELECTION IN THE F_1 GENERATION

One varietal cross, made for the purpose of combining certain desirable characters of the parents, has been carried through the F_2 generation. Kohler, in 1910, crossed the Sir Walter Raleigh variety with an unnamed variety from South America for the purpose of securing a variety more resistant to tipburn. Sir Walter Raleigh, like the rest of the varieties in the Rural group, is less frequently injured by tipburn than most of our other commercial varieties. The foliage of the South American variety was even better in this respect than that of Sir Walter Raleigh.

Some of the results of this cross have been published by the writer (22), and the difficulties involved in the use of parent material which is heterozygous and in which pollen sterility is present, have been pointed out. The results will be summarized here and the more recent data from studies made of the F_2 generation will be presented.

The F_1 generation was very variable, owing to the heterozygous condition of the parent varieties. Segregation occurred in practically all of the important varietal characteristics such as habit of vine growth, type of foliage, time of maturity, coloration of stems, color of flowers, color of tubers, color of sprouts, shape of tubers, and depth of eyes. Sixty-six of the 108 F_1 seedlings were discarded the second year. Six of the 42 seedlings which were grown the third year set seed and 3 of these seedlings were selected as parents for the F_2 generation. In a preliminary progeny test one of the 3 parents appeared the most promising and a total F_2 progeny of 2400 seedlings was grown in 1922. A study of these seedlings was made to determine if their performance the first year grown from seed could be used as a basis for selection.

SELECTION IN FIRST YEAR SEEDLINGS

Stuart (50) mentions that selection can begin at the time of harvesting the first year seedlings. He states that all plants which have irregular tuber progeny, tubers with deep eyes, tubers with undesirable color, or too numerous tubers, should be immediately discarded. The F_2 population of the cross between Sir Walter Raleigh and the South American variety was uniformly good for these characters but there was considerable variation in amount of vine growth, yield of tubers, and time of maturity. A study was made to determine if these characters in first-year seedlings were sufficiently representative of the genotypes of the seedlings to enable the elimination of the weak and late maturing seedlings in their first year without discarding too many valuable plants.

Each seedling was arbitrarily rated the first year for vigor of vine by placing it in one of three classes, namely, weak, medium vigorous, and vigorous. (See Fig. 2.) The seedlings were rated for yield in a similar manner at the time of harvest. Time of maturity was obtained by recording the maturity of the plants every two weeks. The second year the seedlings were rated at various stages of growth for vigor of vine. The first rating was secured by measuring height of seedlings. Yield was secured for the first 500 seedlings by weighing the tubers produced. An arbitrary rating for yield was made on the remainder of the seedlings with sufficient numbers of the weighed progeny included to allow for a comparison of the two methods.

TABLE VIII

CORRELATION BETWEEN VIGOR OF VINE GROWTH, YIELD OF TUBERS, AND PERIOD OF MATURITY OF SEEDLINGS IN THEIR FIRST AND SECOND YEAR

Year	Character	Year	Character	No. of individuals	Coefficient of correlation
1922	Yield	1923	Yield*	487	.343 ± .027
“	“	“	“ †	219	.417 ± .037
“	“	“	“ ‡	168	.539 ± .037
“	Vine growth	“	Vine growth*§	329	.229 ± .035
“	“ “	“	“ “ *‖	403	.329 ± .030
“	“ “	“	“ “ †‖	142	.355 ± .049
“	“ “	“	“ “ ‡‖	85	.260 ± .068
“	Maturity	“	Maturity	568	.525 ± .020
“	Yield	1922	“	3171	.049 ± .009
1923	“	1923	“	326	—.120 ± .037
“	“	1922	“	638	—.001 ± .059
1922	Vine growth	“	“	350	.198 ± .035
1923	“ “ §	1923	“	120	.077 ± .061
“	“ “ ¶	“	“	425	.135 ± .031
“	“ “ ‖	1922	“	558	.120 ± .028
1922	“ “	“	Yield	1940	.601 ± .010
1923	“ “ §	1923	“	327	.382 ± .034
“	“ “ ‖	“	“	426	.341 ± .029
“	Weighed yield	“	Estimated yield	333	.737 ± .017

* Seedlings were taken regardless of their time of maturity.

† Seedlings were taken which matured between Aug. 21 and Sept. 11, 1923.

‡ Seedlings were taken which matured between Sept. 11 and Oct. 4, 1923.

§ Determination of vine growth in 1923 was made at 60 days after planting.

‖ Determination of vine growth in 1923 was made at 90 days after planting.

The degree of relationship for the expression of the characters for the two years was ascertained by means of the coefficient of correlation. While data have been obtaind on 2400 seedlings, only a random sample has been used in the calculations. The coefficients of correlation are here summarized.

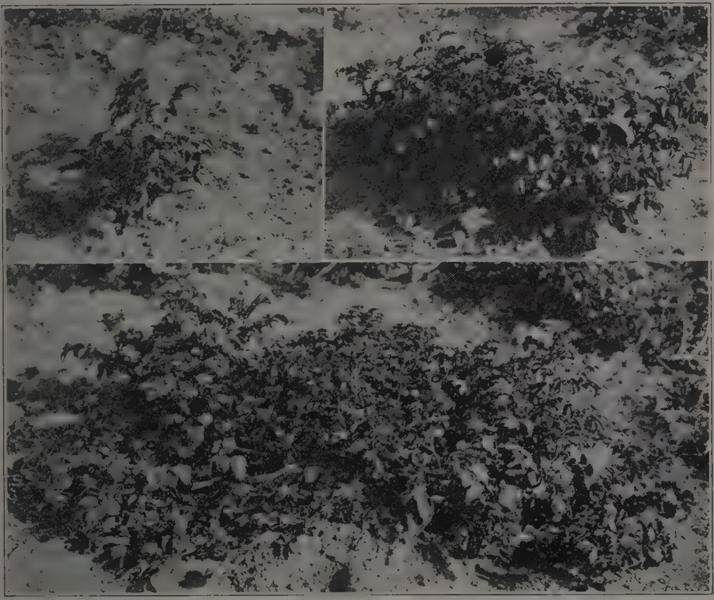

Fig. 2. Representative Seedlings of the Three Classes into Which They Were Divided in Their First Year
Upper left, Weak Upper right, Medium Vigorous. Lower, Vigorous

TABLE IX
Correlation Between Period of Maturity the First Year and Period of Maturity the Second Year in Seedlings

Period of maturity in 1922	Period of maturity, 1923 –8/21	8/21–9/11	9/11–10/4	10/4+	Total
– 9/12	25	11			36
9/12– 9/23	16	18	3		37
9/23–10/ 9	43	108	32	2	185
10/ 9+	21	94	134	61	310
	105	231	169	63	568

r=.525±.025

A high coefficient of correlation (.525±.025) was obtained between the relative period at which seedlings matured in their first year and in their second year. Table IX shows that the relative period of maturity for different groups of seedlings in their first year is fairly representative of the relative period of maturity in their second year. The data show that the time required for a seedling to mature in its first year is of value in determining its genotypic condition in respect to the length of growing season it requires. The correlation for yield for the two years was lower than that for period of maturity. As the yields are based on individual plants, there is a large error involved. The coefficient of correlation indicates, however, that the yield of individual seedlings in their first year gives some idea of their yielding ability the second year.

TABLE X

CORRELATION BETWEEN YIELD OF SEEDLINGS IN FIRST YEAR AND YIELD IN SECOND YEAR

Group rating of yield in 1922	Yield in pounds in 1923										
	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	Total
1	30	27	33	17	5	2	2				116
2	27	52	73	63	38	14	10	1			278
3	3	8	17	19	28	9	5	3		1	93
	60	87	123	99	71	25	17	4		1	487

r=.343±.027

The data on yield in Table X indicate that the relative yielding ability of different families of seedlings in their first year gives some indication of what they might be expected to yield the second year. The reliance that can be placed on the yield of seedlings in their first year will depend on the results of further tests under conditions where sufficient stock of each seedling is available for an adequate field test. These preliminary results suggest that the yield of seedlings in their first year may be of sufficient value for selection purposes to justify further studies of their true significance.

The vigor of vine growth in 1922 was compared with two determinations of the vigor of vine growth in 1923. One of the determinations was made 60 days after planting, the other 90 days after planting. The correlation for the two years was .229±.035 when the determination taken at 60 days after planting in 1923 was used, and .329±.030 when the determination made at 90 days after planting was used.

The correlation between the vigor of vine growth in the first and second year was not significantly different when all the seedlings were considered regardless of time of maturity from that when only seedlings which matured during the same period were considered. The value of r in the first case was .329±.030. When seedlings which matured in the second year between August 21 and September 11 were taken, r was equal to .355±.049; and for seedlings which matured between September 11 and October 4, r was equal to .260±.068.

TABLE XI

Correlation Between Yield and Vigor of Vine Growth 90 Days After Planting in Second Year Seedlings

	Vigor of vine growth in 1923							
Yield in pounds in 1923	1	2	3	4	5	6	7	Total
0.5	3	18	36	11	20	3	1	92
1.5		4	21	21	34	16	6	102
2.5			16	23	27	18	6	90
3.5			2	19	34	16	1	72
4.5			1	15	18	19	3	56
5.5				1	5	3	2	11
6.5					1	1		2
7.5						1		1
	3	22	76	90	139	77	19	426

r = .341 ± .029

TABLE XII

Correlation Between Vine Growth of Seedlings in Their First Year with Vigor of Vine Growth 90 Days After Planting in Their Second Year

	Vigor of vine growth in 1923							
Vigor of vine growth in 1922	1	2	3	4	5	6	7	Total
1	1	7	27	20	21	4	2	82
2	2	6	28	40	73	29	7	185
3		4	13	21	36	42	20	136
	3	17	68	81	130	75	29	403

r = .329 ± .030

TABLE XIII

Correlation Between Yield and Vigor of Vine Growth in First-Year Seedlings

	Group rating of yield in 1922			
Vigor of vine growth in 1922	1	2	3	Total
1	249	171	3	423
2	212	737	72	1021
3	28	284	184	496
	489	1192	259	1940

r = .601 ± .010

TABLE XIV

Correlation Between Vigor of Vine Growth and Period of Maturity in First-Year Seedings

	Period of maturity in 1922				
Vigor of vine growth in 1922	–9/12	9/12–9/23	9/23–10/9	10/9+	Total
1	18	6	24	40	88
2	11	9	68	81	169
3		3	34	56	93
	29	18	126	177	350

r = .198 ± .029

TABLE XV

CORRELATION BETWEEN YIELD AND PERIOD OF MATURITY IN FIRST-YEAR SEEDLINGS

Group rating of yield in 1922	Period of maturity in 1922 –9/12	9/12–9/23	9/23–10/9	10/9–10/23	10/23+	Total
1	83	109	222	266	221	901
2	107	163	480	593	585	1928
3	4	4	56	90	188	342
	194	276	758	949	994	3171

r=.049±.009

TABLE XVI

CORRELATION BETWEEN PERIOD OF MATURITY AND VIGOR OF VINE GROWTH IN SECOND-YEAR SEEDLINGS

Period of maturity in 1923	Vigor of vine growth in 1923 1	2	3	4	5	6	7	8	Total
– 8/21		3	15	22	24	14	1		79
8/21– 9/10	2	6	26	52	57	52	10		185
9/10/10–4	1	2	18	25	31	36	6	1	120
10/ 4+		1	5	5	12	16	2		41
	3	12	64	104	124	98	19	1	425

r=.135±.031

TABLE XVII

CORRELATION BETWEEN PERIOD OF MATURITY AND YIELD IN SECOND-YEAR SEEDLINGS

Period of maturity in 1923	Yield in pounds in 1923 0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	Total
– 8/21	1	19	21	14	9				64
8/21– 9/10	16	24	34	31	31	7	2		145
9/10–10/4	18	20	18	13	13	1	1	1	85
10/4	10	11	6	4	1				32
	45	74	79	62	84	8	3	1	326

r=–.120±.033

A higher correlation between vigor of vine growth and yield was obtained in seedlings in their first year than in their second year. This is shown by a comparison of Tables XI and XIII. The difference obtained in the two years was due to the late maturity of a portion of the seedlings. In these seedlings the vines were frosted before they had an opportunity to express their vine growth in yield of tubers. A study of Table XVII shows that the seedlings which were green at time of harvest gave the lowest average yield of tubers. The vigor of vine growth of these seedlings was fully equal to the earlier maturing seedlings, as is shown in Table XVI. The same condition occurred in the seedlings in their first year but to a lesser degree.

A study was made to determine if an arbitrary rating for yield by inspection in second year seedlings approached the weighed yields sufficiently to justify this method of determining the yield. The coefficient of correlation between the two methods was .737±.017. The results of the two methods in this experiment were in close agreement, and for the purpose of selection in a large population, yield ratings were as satisfactory as the weighed yields.

It is important to know what degree of reliability can be placed on the expression of characters of commercial importance in first year seedlings. The elimination of undesirable seedlings in their first year would eliminate the expense of growing them a second year and would also enable a more careful study to be made of the desirable seedlings. The results presented on period of maturity and vigor, as expressed by amount of vine growth and yield, show that there is a positive correlation between the two years, in the expression of these characters.

In certain cases as, for instance, in testing for desirable F_1 combinations of inbred strains, it would appear that the data obtained on the seedlings in their first year would be a reliable guide as to which of the F_1 combinations are promising.

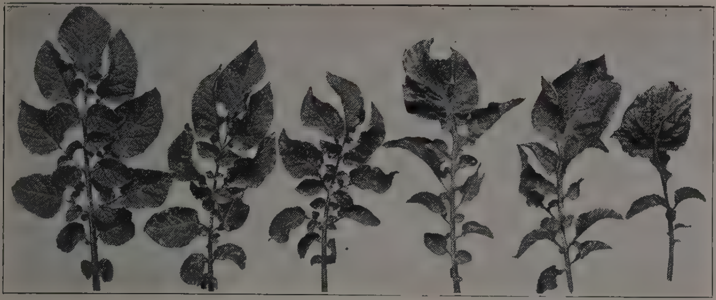

Fig. 3. Abnormal Leaf Type Which Appeared in One of the Selfed Potato Lines
Left, Normal leaves Right, Abnormal leaves

SELECTION IN SELF-FERTILIZED LINES

Inbreeding studies on maize by East (5) and Shull (41, 42, 43, 44) suggested to these investigators the value of selection in self-fertilized lines of normally cross-pollinated crops as a means for their improvement. Later studies by Hayes and Garber (16), Hayes (14), East and Jones (9), and Jones (19, 20) have not only established its value but have given practical demonstrations of improvement through this method. Briefly, the method consists in selecting the most desirable genotypes in self-fertilized lines. The decline in vigor which accompanies the approach to homozygosity is regained by subsequent crossing of inbred strains which possess different genotypes. F_1 individuals in maize from these inbred strains have shown greater vigor than the original parents. This increased vigor may be due to a partial dominance of growth factors in the F_1 or to the absence in the F_1 individuals of deleterious growth factors which have been eliminated from the genotypes of the parents by selection in the self-fertilized lines, or by a combination of the two causes. In a vegetatively propagated crop such as the potato, in which the resultant heterozygous F_1 individuals can be propagated indefinitely, the method would appear to be particularly appropriate. Furthermore, the almost total absence of desirable parents among our present potato varieties which produce viable pollen, makes it imperative to utilize some method to secure the parents necessary for a basis for potato breeding work.

EFFECT OF INBREEDING ON HETEROZYGOSITY

Self-fertilized lines have been started from numerous varieties for the purpose of securing more desirable parental material. Some of the lines have been selfed for one generation, others for two generations, and a few for three generations.

An unnamed variety obtained from Mexico has been selfed for three generations. The first generation of seedlings of this variety was more variable than the first generation of fifteen other varieties studied. The results obtained with this variety are illustrative of how better breeding material can be obtained through selection in self-fertilized lines.

In haulm characters the first generation varied in amount of vine growth, habit of growth, size and coloration of stems, size of leaves, and appearance of leaflets. The tubers varied in size and shape. One seedling was described by Kohler as having "small, gnarly, absolutely worthless tubers." Other seedlings gave more promising tubers and in later generations some lines having a desirable type of tubers were obtained. The seedlings varied in tuber color from dark purple through the varying shades of purple and red to white. Some seedlings had tubers with red eyes, others had tubers which were completely white. The second generation progeny from one first generation seedling was less variable than the first, altho in certain foliage characters some of the seedlings were quite distinctive. A few seedlings produced tubers that were slightly pink at the seed end. In other tuber characters the seedlings were similar. F_3 seedling progeny were grown from three second generation seedlings. The distinctive variations in characters which characterized the first generation were no longer present in these third generation seedlings. That the commercial varieties of potatoes are extremely heterozygous is well known and needs no further emphasis. Certain undesirable characters such as short internodes, prostrate plants, simple leaved types, seedlings deficient in chlorophyl, and numerous seedlings with tuber abnormalities have appeared in selfed lines. Most of them are recessive and are not exhibited by the parents. Salaman (32, 33, 34) has shown that the tuber characters which are important from the commercial standpoint are inherited in a relatively simple manner. The tuber defects of varieties have been found easy to eliminate in instances in which the variety was heterozygous for these characters. In fact, a striking feature of the results obtained in the three varieties which have been selfed for more than one generation has been the apparent ease with which undesirable plant and tuber characteristics have been eliminated.

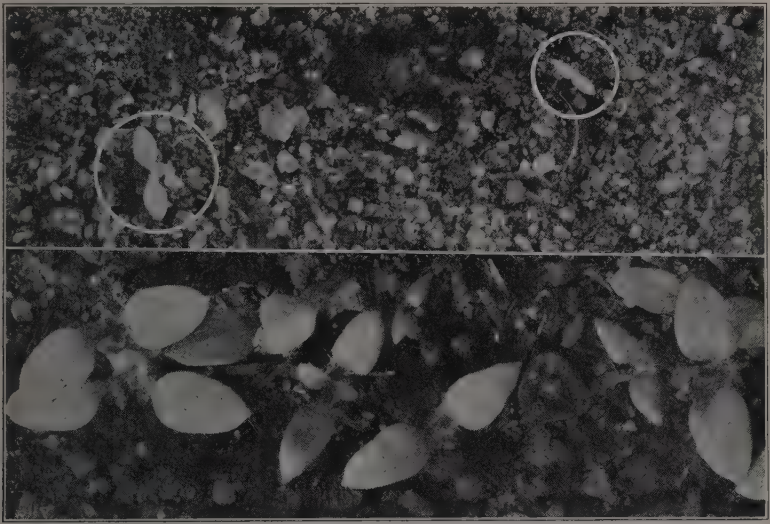

Fig. 4. Seedlings in Selfed Lines of Potatoes
Above, seedlings lacking chlorophyl; below, normal seedlings

TABLE XVIII
CONDITION OF MATURITY OF FIRST GENERATION SEEDLINGS AND OF THE PROGENY OF SOME OF THESE FIRST GENERATION SEEDLINGS

Parent		Number of individuals mature and immature on Sept. 10			Percentage of individuals mature and immature on Sept. 10	
		Mature	Immature	Total	Mature	Green
14329	Parent plant	9	31	40	22.5	77.5
14329– 8	1st generation seedling	1	13	14	7.4	92.8
14329–16	1st generation seedling	5	43	48	10.4	89.6
14329–45	1st generation seedling	5	40	45	11.1	88.9
14329– 4	1st generation seedling	5	21	26	19.2	80.8
14329–44	1st generation seedling	14	23	27	37.8	62.2
14329–55	1st generation seedling	19	25	44	43.2	56.8
14329–26	1st generation seedling	16	19	35	45.7	54.3
14329–10	1st generation seedling	11	13	24	45.8	54.2
14329–40	1st generation seedling	13	13	26	50.0	50.0
14329– 1	1st generation seedling	20	13	33	60.6	39.4
14329–18	1st generation seedling	23	3	26	88.5	11.5

ISOLATION OF EARLY AND LATE MATURING LINES

An example of how a complex character such as maturity segregates may be noted by observing the differences in maturity in lines obtained from a parent heterozygous for this character. (See Table XVIII.)

In Table XVIII are given the results of a progeny test showing that lines which are genotypically earlier and later maturing than the parent variety may be obtained from a parent heterozygous for time of maturity. The number of seedlings in each line that had matured and the number that was still green on September 10 are given. In the last two columns the results are presented in percentages. A study of Table XVIII shows that the percentage of the progeny of different lines which mature on September 10 varied from 7.4 to 88.5. The original parent was intermediate in time of maturity, as 22.5 per cent of its progeny matured by September 10. Variations from the illustration occur, depending on the genotypic condition of the parent and the number of factors responsible for the particular character.

Fig. 5. General View of Potato Breeding Plot, 1922

EFFECT OF INBREEDING ON VIGOR

As the lines have become more homozygous, a reduction in vigor of the seedlings has usually occurred. A study of Table XIX, which gives a comparison of amount of vine growth and yield of tubers between the first and second generation of selfed seedlings of U. S. D. A. seedlings 14329, shows that the second generation was less vigorous in vine growth and yielded fewer tubers than the first generation. The average height of the first generation seedlings in centimeters on July 2 was 19.9±0.7 and of the second generation 16.5. The average estimated yield of first generation seedlings was 5.25±.20 and the average yield of second generation lines was 3.8. Some second generation lines approached the first generation in vigor. Other lines were distinctly less vigorous. Selfed lines from two other varieties are also shown in Table XIX. Selfed lines of the third generation of an unnamed variety from Mexico, No. 64, were very vigorous. They were equal in vigor to the F_1 seedlings of varietal crosses. (See Table VII.) Seed of this variety for the first and second generation was not available for a test to determine the relative vigor of the three generations. Seed tubers of seedlings of these generations are on hand for a comparative test in 1924.

TABLE XIX

Effect of Inbreeding on Vigor of Vine Growth and Yield of Potatoes

Parent	Generation	Av. height of seedlings, in cm., July 2	Av. amount of vine growth, Aug. 2	Av. amount of vine growth, Sept. 1	Av. yield of seedlings, Sept. 10
U.S.D.A. Seedling 14329	first	19.9±0.7	4.25±.21	4.8±.28	5.25±.20
14329–1	second	16.9±1.0	4.0±.30	3.5±.40	4.2±.27
14329–4	"	13.7±1.4	4.0±.43	3.5±.48	3.5±.38
14329–8	"	9.5±1.2	2.0±.35	3.5±.48	2.6±.38
14329–10	"	19.5±1.4	4.0±.43	4.7±.48	4.0±.38
14329–18	"	21.0±1.0	3.0±.30	4.4±.48	3.3±.31
14329–40	"	16.2±1.0	4.0±.30	4.7±.40	3.2±.27
14329–44	"	14.7±1.0	5.0±.30	5.8±.40	5.1±.27
14329–45	"	19.5±1.0	4.0±.30	4.5±.40	3.1±.27
14329–55	"	17.9±1.0	4.7±.30	4.9±.40	4.5±.27
14329–66	"	14.9±1.2	4.7±.35	5.0±.40	5.1±.31
14329–26	"	18.0±1.4	5.5±.43	5.2±.48	4.0±.38
Average	"	16.5	4.1	4.5	3.8
Pearl variety	"				
88–3	"	21.3±1.0	5.0±0.30	....	5.0±.31
88–4	"	11.6±1.0	4.5±0.30	....	4.4±.31
Average	"	16.4	4.7	..	4.7
Unnamed variety from Mexico	third				
64–3–1	"	23.0±2.0	8.0±0.60	....	....
64–3–8	"	24.3±1.0	6.0±0.30	....	5.1±.38
64–3–11	"	22.0±1.2	5.0±0.35	....	5.0±.31
Average	"	23.1	6.3	..	5.25

STERILITY IN RELATION TO INBREEDING

The utilization of the method of selection in self-fertilized lines depends on securing fertile progeny. Salaman and Lesley (35) have shown that sterility is inherited only through the female parent. They have also furnished evidence to indicate that sterility is dominant to fertility with a number of factors involved. In the present studies it has been found that varieties which are dependable as a source of pollen for crossing will produce some fertile progeny when self-fertilized. Two of the standard commercial varieties, Green Mountain and Early Ohio, have produced fertile seedlings in their progeny grown from self-fertilized seed. The Green Mountain variety usually sets some seed under favorable growing conditions. The Early Ohio variety usually sets no seed. It apparently produces viable pollen only under very favorable conditions. To what extent self-fertilization is possible with lines obtained from the varieties which seldom set seed, is uncertain. The results so far obtained indicate that continued self-fertilization may be possible in some lines derived from these varieties.

The preliminary results obtained from selection in self-fertilized lines have been encouraging. The progress is necessarily slow because it usually requires two years to grow a generation from seed to seed. Immediate benefits, however, have been obtained. The first generation of selfed seedlings has invariably produced better parental material than the original parent. The results obtained from the second and third generation show that seedlings homozygous for the characters which are of economic importance can probably be secured in three or four generations. As a means of obtaining improved female parents that are superior for breeding purposes to our present commercial varieties and pollen parents that are superior to those previously available, the method of selection in self-fertilized lines can be fully justified. The average vigor of the second generation was found to be below the average vigor of the seedlings of the first generation. From the results obtained by investigators in maize, a reduction in vigor as a result of self-fertilization can probably be expected as the selfed lines approach homozygosity. The vigor exhibited by the F_1 seedlings of varietal crosses justifies the belief that the reduced vigor of seedlings from selfed lines can be recovered by crossing inbred strains.

CONCLUSIONS

The few critical studies that have been made in the potato support the view that Johansen's pure line theory can be applied to the asexual progeny of a potato seedling. There is no published experimental evidence to the contrary. To the plant breeder, as a rule, selection in such pure lines is of no practical value. The large amount of clonal selection work on the potato has made no appreciable improvement in our potato varieties. This appears to be strong evidence that the method of clonal selection does not offer reasonable hope for the further improvement of potato varieties.

The present evidence does not support the conclusion that numerous strains, as represented by seed stocks of different growers, exist within the variety. The fact that variations in yield between seed stocks of a variety are obtained, is not necessarily proof that such variations are due to hereditary differences between the seed stocks of the variety. Degeneration diseases, storage, and soil heterogeneity are important causes of variations in yield that have frequently been given inadequate consideration.

The increased vigor of the F_1 over the seedlings of the selfed parents suggests that improvement may be secured by this means. The use of the F_1 at the present time is of little value, on account of the absence of desirable varieties which possess dependable pollen.

The presence of sterility will probably not prevent obtaining F_2 populations from most crosses. Their use is limited on account of the scarcity of desirable parents which produce viable pollen. Owing to that heterozygous condition of potato varieties, it may be necessary to grow a number of F_2 populations from different F_1 seedlings in order to obtain an individual having the desired combination of characters. Improved varieties that are dependable as pollen parents are a necessary requisite to any great improvement in the potato varieties of this country. Selection in self-fertilized lines is the best method of obtaining such varieties.

SUMMARY OF EXPERIMENTAL RESULTS

1. Two seed stocks of the Early Ohio variety in which the grower had practiced selection for productivity and type for 20 or more years were found to be the same as the normal for the variety as far as could be ascertained by a careful comparison for four years with five other seed stocks. The variability of yields between seed stocks within the variety, as judged by 84 separate seed stocks of the variety, was not significantly greater than the variability within a single seed stock. The results show that soil heterogeneity was the cause of the variability in yield.

2. Variations in the tuber form of seed stocks of a variety were found to be due to differences in conditions under which they were grown. They were found to be non-heritable. When the ratio of width to length of the tubers was used as an index to shape, there was found to be no correlation between shape of original tuber stock and that of the progeny when grown under different conditions. This is indicated

by the coefficient of correlation —.004±.127. Similarly, correlation was lacking when the shape index ratio of depth to width was used. The coefficient in the case being —.049±.157.

3. The seedlings of F_1 varietal crosses were more vigorous than the seedling of the parents which were obtained by using selfed seed. The increase in vigor was expressed in both the amount of vine growth and the yield of tubers. A cross between Sir Walter Raleigh and an unnamed variety from South America was carried into the F_2 generation. In this particular cross between a variety producing medium or small amount of viable pollen and a variety producing abundant pollen, it was possible to select desirable F_1 plants which produced an abundance of self-fertilized seed. It made possible the selection of desirable parents for the F_2 generation.

4. The characters of period of maturity and vigor in first year seedlings as judged by amount of vine growth and yield were found to be correlated with their behavior the second year. The evidence presented shows that the time of maturity and vigor of seedlings in their first year may be sufficiently representative of their later behavior that certain groups of seedlings can be eliminated after the first year.

5. Selection in self-fertilized lines was found to be a practical method of securing improved parental material. A comparison of first and second generation seedlings showed that as the seedlings became more homozygous a reduction in vigor occurred.

6. The results obtained in this study of methods in potato breeding lead to the conclusion that selection within self-fertilized lines with subsequent crossing of the inbred individuals is the most promising and the most practical method for the further improvement of potato varieties.

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The University of Minnesota
Agricultural Experiment Station

IN CO-OPERATION WITH

UNITED STATES DEPARTMENT OF AGRICULTURE,
BUREAU OF AGRICULTURAL ECONOMICS

Economic Aspects of Creamery Organization

John D. Black and Edward S. Guthrie
Division of Agricultural Economics

UNIVERSITY FARM, ST. PAUL

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ECONOMIC ASPECTS OF CREAMERY ORGANIZATION

By John D. Black and Edward S. Guthrie[1]

This bulletin deals more especially with the problems of organization of creameries as distinguished from the problems of management. Of the three phases of organization, namely, economic organization, financial organization, and business organization, it considers the first. Its conclusions should be of value to some operators and managers of creameries and some members of creamery organizations, in helping them to establish efficient creamery enterprises or re-organize existing enterprises along more efficient lines; but the bulletin in its present form is intended primarily for specialists in the field of marketing and dairy manufacture.

SOURCES OF DATA

The data in this bulletin are partly from official sources, such as the records of the Minnesota Dairy and Food Department,[2] but mostly from a special survey made of 102 Minnesota creameries. In most of the tables the data from only 88 of these 102 creameries are used.

THE STATE

On January 1, 1920, Minnesota had 1,229,000 cows two years old and over, classified as "kept primarily for milk," ranking third after Wisconsin with 1,795,000, and New York with 1,482,000. Per 1000 acres of land in farms, Minnesota with 41 ranks after Wisconsin with 81, New York with 72, New Jersey with 57, Pennsylvania with 50, Michigan with 42, and the New England States taken as a group with 50. Per 1000 acres of improved land in farms, Minnesota ranks after the same states, but with only 57 as against 144 for Wisconsin, 113 for New York, 75 for Pennsylvania, and 66 for Michigan. In 1919, with relatively low butter prices, approximately fifteen per cent of the average gross income of Minnesota farms was from dairy products.[3] For a normal year, 18 per cent is about right. As to milk production per cow, Minnesota ranks below all the New England States, all the North Atlantic States, and all the North Central States. The estimates obtained by the Bureau of Crop Estimates in June, 1920, indicate that 33.2 per cent of all of the cattle of Minnesota were Shorthorn, as compared with 29.8 per cent for the dairy breeds. (Holstein, 19.3 per cent.) In Wisconsin, 16 per cent were Shorthorn, as compared with 72.2 per cent for the dairy breeds. In New York, 89.1 of the cattle were of the dairy breeds. In Minnesota, 13.8 per cent of the cattle were "nondescript" or "scrubs," in Wisconsin 7.0 per cent, in New York 5.9 per cent.

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[1] Dr. Guthrie did the field work on this study during the summer and fall of 1920, while on sabbatical leave from Cornell University.

[2] The authors wish to thank the staff of the Dairy and Food Department for their very great courtesy and excellent co-operation; also R. C. Potts of the Bureau of Agricultural Economics, and C. H. Eckles and J. R. Keithley for their help in outlining the project and preparing the results for publication; also A. J. McGuire, general manager of the Minnesota Co-operative Creameries Association, Inc.

[3] This can be only a rough approximation, as the Census Bureau did not tabulate all the data on farm receipts for 1920.

There is undoubtedly a tendency toward the dairy breeds and more dairying in many parts of Minnesota; but the 1920 census was not taken in such a way as to show it.

In 1920 the creameries of Minnesota made 139,230,000 pounds of butter as compared with 95,668,000 pounds in 1910. Butter made on farms in the same period decreased from 35 to 20 million pounds; and butter sold from farms from 18 to 4 million pounds. Cheese production in the same period increased only from 3,800,000 to 3,848,000 pounds. Thus by turning nearly all its surplus milk into butter, Minnesota has become the leading butter state in the Union.

In 1920, there were 830 creameries in Minnesota, 642 of which were co-operative. The co-operative creameries made 67 per cent of all the factory-made butter, the centralizers 24 per cent, and the other proprietary creameries 10 per cent. The co-operative creameries are gradually gaining upon the proprietary creameries, as in 1914 the co-operatives made only 62 per cent of the butter.

In 1920, the creameries received 168 million pounds of milk and 390 million pounds of cream. Thus more than 90 per cent of all the butterfat was delivered as cream. A considerable portion of the milk received by creameries is resold as market milk. Milk receipts are still rapidly declining.

Minnesota, however, has such a variety of systems of farming that its dairying must really be analyzed by districts. In Figure 1 and Figure 2 the state is divided into 8 districts. Figure 1 also shows the location of all creameries and cheese factories. Tables I and II give the principal data for each district. The southern dairy section and the Red River Valley represent the two extremes. In the southern dairy section, the creameries in 1919 averaged 125,000 pounds of butterfat per creamery, received 58.3 cents per pound for their butter, and paid their patrons 66.8 cents per pound for butterfat. Nearly 4000 pounds of butterfat were delivered to the creamery per square mile of territory, an average of 120 pounds per cow. In the Red River Valley, the creameries averaged only 63,000 pounds of butterfat, received only 54 cents per pound for butter, and paid their patrons only 58.7 cents per pound for butterfat.

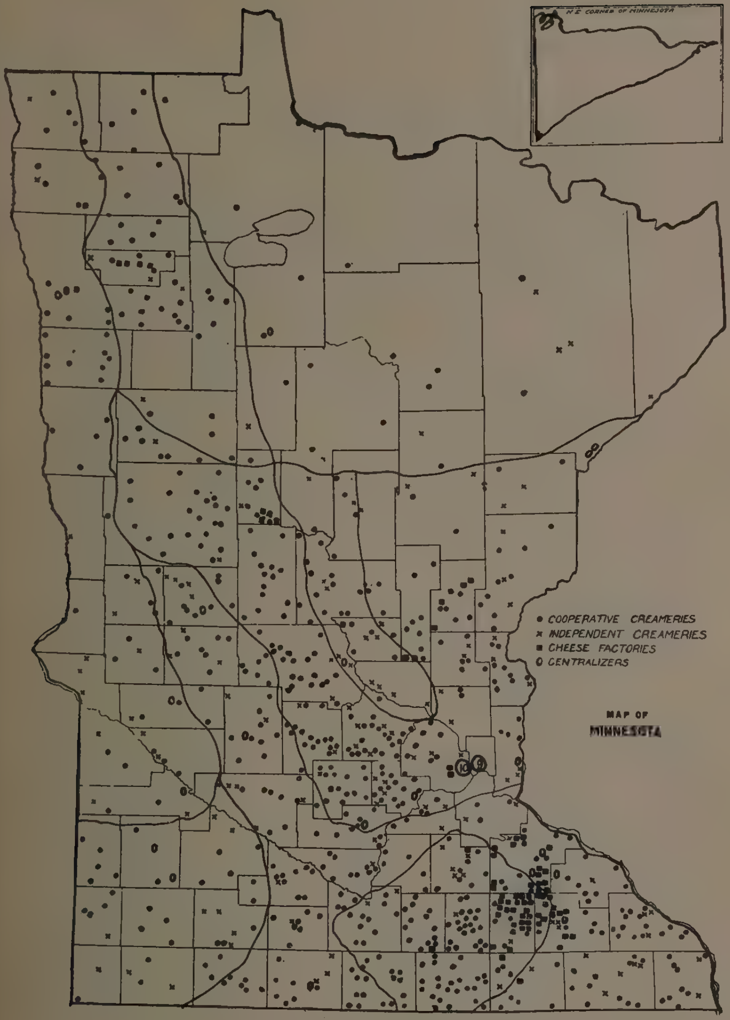

Fig. 1. Localization of Dairy Manufacturing in Minnesota

The only part of Minnesota where a genuine dairy type of farming is practiced is in a broad belt extending from north to south through the center of the state. Independents and centralizers handle much of the cream outside of this belt, and in some parts of this belt the cheese factories compete on strong terms with the creameries.

TABLE I

COMPARISON OF THE EXTENT OF DAIRYING IN VARIOUS SECTIONS OF MINNESOTA

Name of section	No. of counties in section	Farm receipts from dairy products*	Butterfat delivered per cow†	Butterfat per square mile‡
		Per cent	Lbs.	Lbs.
I. Southern dairy	6	20	120	3893
II. Central dairy	18	20	104	2981
III. Intermediate dairy	21	14	108	1921
IV. Mississippi Valley	3	20	105	1765
V. Southwestern corn	8	11	94	939
VI. Red River Valley	13	8	92	913
VII. Northwestern dairy	6	16	96	1607
VIII. Cut-over	11	16	79	663
State	86	15	102	1835

* Based on Census of 1910. This figure can not be computed for 1920, because the Census Bureau did not tabulate data on sales of livestock and crops.

† According to the records of the Dairy and Food Department, centralizers being omitted. Milk consumed on the farm is not included. The 1920 Census estimates represent a state average of 132 pounds of butterfat per cow for all uses, as compared with the 102 pounds delivered to creameries, as given in this table.

‡ Based only on the 102 creameries visited. Butterfat per square mile delivered to creameries, not including milk delivered to centralizers, cheese factories, or sold directly to cities for consumption as whole milk.

TABLE II

COMPARISON OF CREAMERIES IN VARIOUS SECTIONS OF MINNESOTA, 1919*

Name of section	Number of creameries			Average butterfat per creamery*	Price received for butter†	Price paid patrons for butterfat	Margin per pound of butter‡	Overrun
	Co-operative	Independent	Centralizers					
				Lbs.	Cents	Cents	Cents	Per cent
I. Southern dairy	93	6	0	124,379	58.3	66.8	4.0	22.95
II. Central dairy	178	41	21	118,913	58.7	66.5	4.8	23.39
III. Intermediate dairy	189	43	10	109,164	56.0	63.0	4.6	22.57
IV. Mississippi Valley	22	9	0	114,181	54.8	61.8	4.7	23.39
V. Southwestern corn	23	11	3	101,801	54.3	60.1	5.1	22.13
VI. Red River Valley	49	15	3	63,064	54.0	58.7	5.9	22.03
VII. Northwestern dairy	39	7	2	81,433	55.8	63.0	5.1	24.26
VIII. Cut-over	30	13	6	53,625	54.3	59.1	5.8	21.86
State	623	145	45	99,348	56.9	64.2	4.8	23.10

* Only independent and co-operative creameries were used in computing these averages—from records of the Dairy and Food Department.

† Transportation costs, commissions and other central marketing expenses having been deducted.

‡ The same as expense per pound of butter, except that profits and patronage dividends are included.

TABLE III

Comparison of Creameries Covered in the Survey, by Sections

Sections	Number of creamery reports used		Average butterfat per creamery	Price received for butter per lb.	Price paid patrons for butterfat per lb.	Expense per pound of butter	Overrun	Average quality of cream*	Score of butter†
	Co-operative	Independent							
			Lbs.	Cents	Cents	Cents	Per cent		
I. Southern dairy	9	..	243,301	57.1	67.4	3.6	22.35	2.2	92.5
II. Central dairy	45	4	198,365	57.0	67.8	4.1	23.56	2.5	91.5
III. Intermediate dairy	14	2	149,128	55.1	62.1	4.1	22.74	3.3	90.5
IV. Mississippi Valley	4	..	167,231	54.7	61.4	4.7	22.71	3.7	89.0
V. Southwestern corn	1	..	105,209	54.3	59.0	4.9	25.29	4.0	90.0
VI. Red River Valley	2	..	107,907	53.3	58.0	5.8	18.54	4.5	89.5
VII. Northwestern dairy	4	..	189,280	55.6	66.7	4.7	24.20	3.3	90.5
VIII. Cut-over	2	2	189,279	56.2	61.0	5.1	22.48	4.5	88.5
State	80	8	168,681	55.4	62.9	4.6	22.73	2.86	90.25

* Average of rankings as to quality of cream at time of survey: Highest quality, rank 1; lowest quality, rank 5.

† Score of butter in refrigerator at time of visit, usually from one to three days old.

Additional facts concerning each of these sections are as follows:

Section 1. Southern dairy section.—Less than half of farm receipts from sale of crops; and more than half of livestock receipts from cattle. Corn acreage 20 per cent of total. Cash crops are spring wheat and barley. Hogs in combination with dairying. Many Holstein herds.

Section 2. Central dairy section.—From 50 to 65 per cent of farm receipts from crops, from spring wheat mostly in the southwest, and potatoes around the Twin Cities and to the north. Livestock receipts mostly from cattle, frequently of dairy types; but some from hogs, especially in McLeod and Kandiyohi Counties.

Section 3. Intermediate dairy section.—Mostly Shorthorn cattle. Large receipts from spring wheat to the north and oats and barley in other counties. Corn and hogs to the southwest.

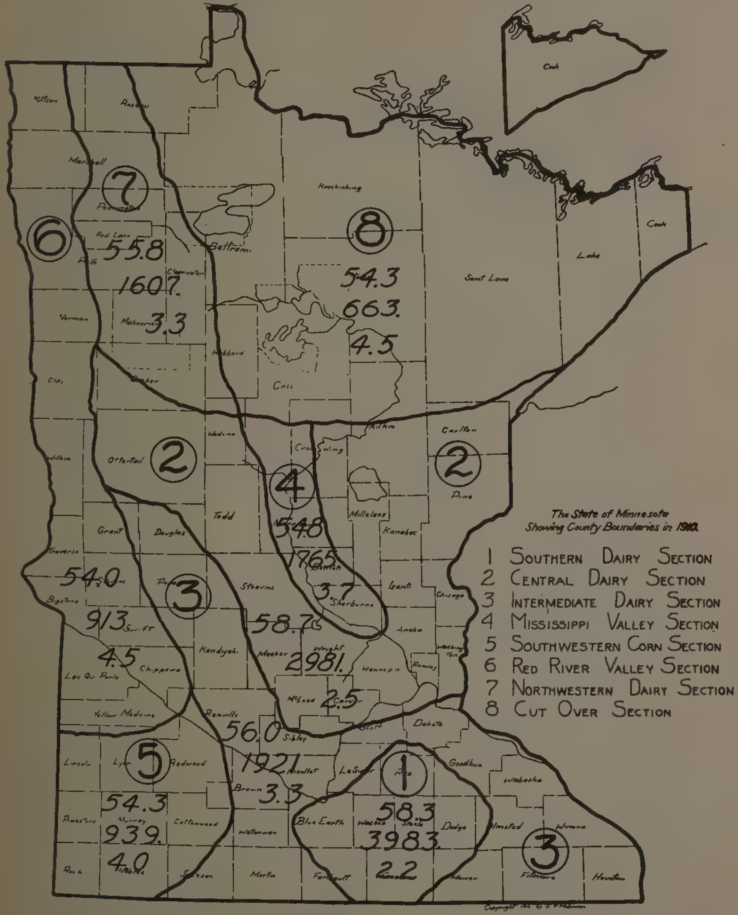

Fig. 2. Minnesota by Dairy Districts

Upper figures—Average price received for butter. Middle figures—Butterfat delivered per square mile. Lower figures—Average rank of creameries by quality of cream delivered. Quality of cream and quantity are closely associated; also quality of cream and price received for butter.

Section 4. Mississippi Valley.—Dairying in combination with potatoes, rye, and small grains on sandy lands. Dairy receipts an important source of income.

Section 5. Southwestern corn section.—Corn and hogs. Oats and barley near the Dakota line. Beef cattle.

Section 6. Red River Valley.—Three-fourths of receipts from sale of crops, mostly spring wheat and potatoes. Beef cattle mostly, and not many of them.

Section 7. Northwestern dairy section.—Relatively new country, much drained land. Hay an important crop. Dairying of high order considering the newness of the region.

Section 8. Cut-over section.—Hay principal crop. Potatoes, timber products, outside labor, and dairy products the principal sources of income. Creameries small and far between.

It should be apparent from the foregoing that it is useless to talk of dairying in Minnesota, taking the state as a whole. The same is true in large part for creameries. This is shown by Table III, which gives certain data for the 88 creameries analyzed in this bulletin. First, the cream received differs greatly in quality,[4] that coming from the Red River Valley and cut-over district actually averaging a condition half-way between "Sour and Old" and "Fairly Sour and Old," and that from the southern dairy section averaging about "Fairly Good." The score of the butter on hand at the time of the survey ranged from 88.5 in the cut-over district to 92.5 in the southern dairy section.

TABLE IV

RELATION OF QUALITY OF CREAM TO QUALITY OF BUTTER

Type of cream	Rank	Number of creameries receiving mostly	Butter score*	Average price received for butter in 1919†	Average output
				Cents	
Sour and old........	5	16	89.6	54.1	140,000
Fairly sour and old..	4	10	89.4	54.7	149,000
Fair	3	34	91.1	56.6	242,000
Fairly good.........	2	10	92.8	57.8	251,000
Good	1	18	92.8	57.9	270,000

* Butter on hand at time of survey.

† Some of the difference in price for the different grades is due to the fact that the creameries receiving poor cream are small and are likely to have relatively poor buttermakers. (See page 16.)

It will be noted that these 88 creameries average about a third larger than the state average (see Table II). Their expenses per pound of butter are therefore somewhat lower. As to the price received for butter, however, they are nearly 2 cents under the average. Of the 14 creameries included in the survey but not included in the tables, 6 are proprietary creameries whose financial records were so incomplete that their data could not be used. The co-operative creameries usually keep better records.

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[4] See Table IV for classes of cream.

FACTORS OF EFFICIENCY

The ultimate test of the efficiency of a creamery is the price it pays for butterfat. Figure 3 shows an extreme range—30 to 49 cents for 291 Minnesota creameries in 1921. No doubt some of the extreme cases are due to irregularities in the records, but making allowance for this, there is still a range, excluding irregular cases, of 16 cents, or 38 per cent. Fifteen cents more or less for butterfat will probably mean the difference between profit and loss in dairying on two thirds of the dairy farms of the state. Part of this 15 cents is of course due to differences in the cream delivered. But enough of it can be ascribed to the creamery that we are justified in saying that the creamery alone is one of the largest factors in the success of dairying, and it is highly important that it be properly organized. Even 10 cents less a pound for butterfat means 14 million dollars for the farmers of Minnesota. The purpose of this bulletin is to present the causes of these variations.

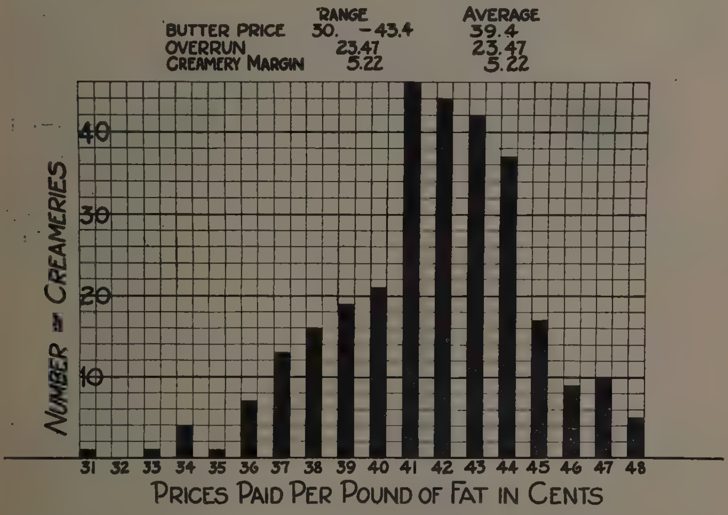

Fig. 3. Range in Prices Paid per Pound of Butterfat for 291 Minnesota Creameries as Reported in 1921

The ordinary range is from 34 to 49 cents; the five extremely low prices are probably due to errors in the creamery records.

There are three immediate reasons for these variations. These are differences in prices received for butter, differences in cost of manufacture and preparation for market, and differences in overrun. Figures 4, 5, and 6 show the ranges for these three things. The range in prices received for butter is the most important factor. Most of the creameries in 1921 received between 35 and 41 cents per pound for their butter, but 16 out of 290 received more than 41 cents and 23 out of 290 less than 35 cents. Figure 7 shows that if there were no differences in overrun or creamery costs[5] per pound, butter price would still produce a range, excluding irregular cases, of 13 cents per pound of butterfat.

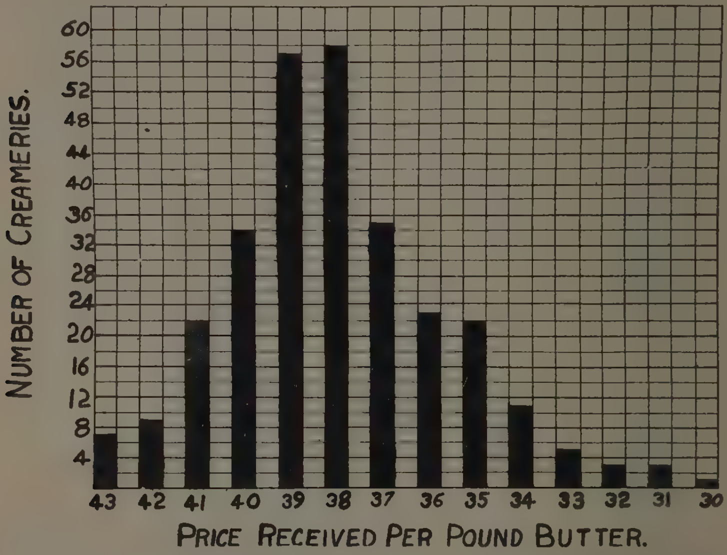

Fig. 4. Ranges in Net Prices Received per Pound of Butter for 88 Minnesota Creameries
The ordinary range in prices received for butter is 11 cents—5 cents less than the range in butterfat prices.

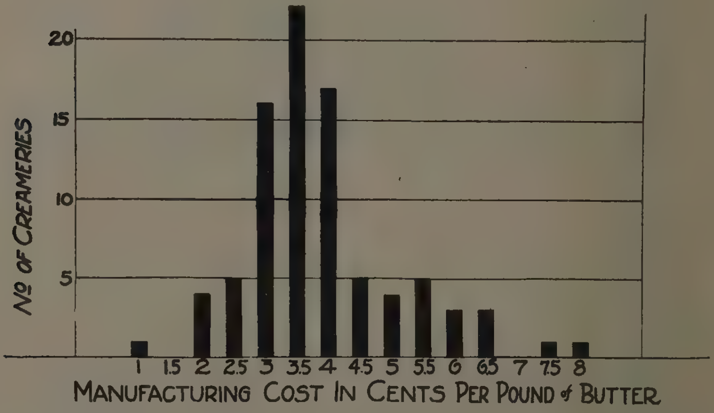

Fig. 5. Range in Manufacturing Costs per Pound of Butter for 88 Minnesota Creameries

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[5] Really "margins," as profits and patronage dividends are combined with costs.

Next in importance are the differences in creamery costs shown in Figure 5. The ordinary range for the 88 creameries covered in the survey is from 2 to 7 cents per pound of butter. (Extreme costs are due in most cases to irregularities in the records.) If prices for butter and overrun were the same for all creameries, differences in creamery costs, as shown by Figure 8, would still make a difference, excluding irregular cases, of 9 cents a pound of butterfat.

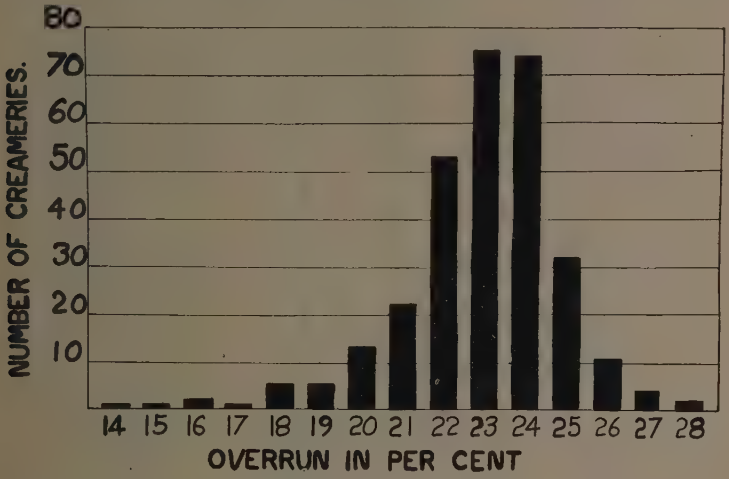

Fig. 6. Ranges in Over-run for 301 Minnesota Creameries

The over-runs, at least over 24 and under 20, are not true over-runs, but are due to errors in tests and weights and mistakes in creamery records.

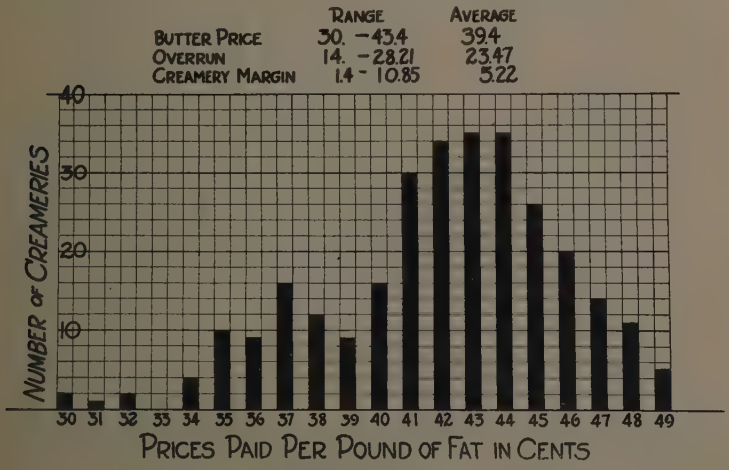

Fig. 7. Relation of Price Received for Butter to Prices Paid for Fat

If all creameries had the same over-run of 23.47, and the same margins, there should still be an ordinary range of 36 to 48 cents in prices paid for butterfat.

The ordinary range in overrun, as shown by Figure 6, is from 20 to 26 per cent. If butter prices and creamery cost were the same for all creameries, there would still be a difference, excluding irregular cases, of 3 cents per pound of butterfat, due to overrun variations (see Fig. 9).

Range in butter prices.—The principal cause of variations in butter prices is the quality of the cream delivered. Table IV shows that the 18 creameries receiving "Good" cream on the day of the visit were making butter scoring 3.2 points higher than that made by the 16 creameries delivering "Sour and Old" cream; and that they sold their year's make of butter for nearly 4 cents more per pound.[6] The possible range due to differences in cream, according to Table V, was 6 cents.

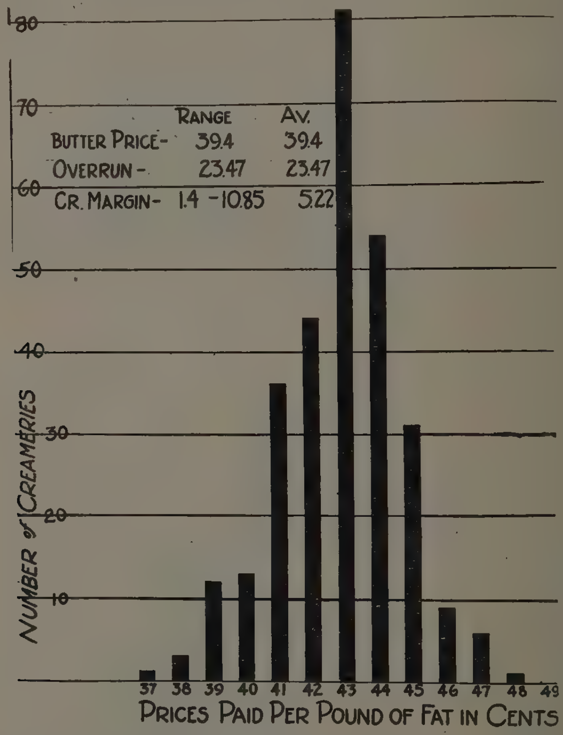

Fig. 8. Relation of Creamery Margins to Prices Paid for Fat

If all creameries received the same prices for butter and had the same over-run, there would still be an ordinary difference of 8 cents in prices paid for butterfat, due to difference in costs or margins.

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[6] The question arises as to how good a sample one day is of the whole year in a matter of this kind. The chances are that there is no great variation from day to day in quality of cream received, and there is much less variation from season to season than is ordinarily supposed. As for quality of butter, there may be a variation of two or even three points in the score, but there is likely to be no more than a point of difference. Moreover, there are enough creameries in each group to make it probable that error of sampling will be offset.

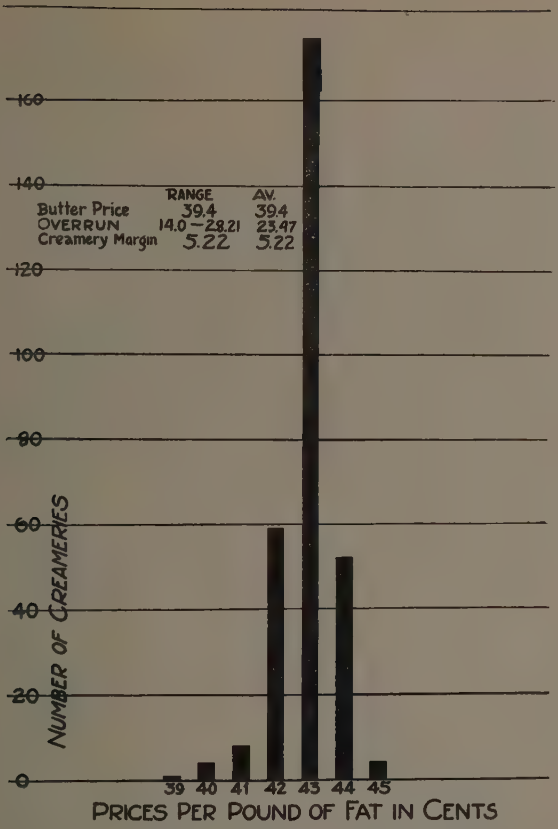

Fig. 9. Relation of Over-run to Prices Paid for Fat

The ordinary effect of differences in over-run is only 3 cents, as compared with 8 cents for costs (Fig. 7) and 13 cents for prices of butter (Fig. 8).

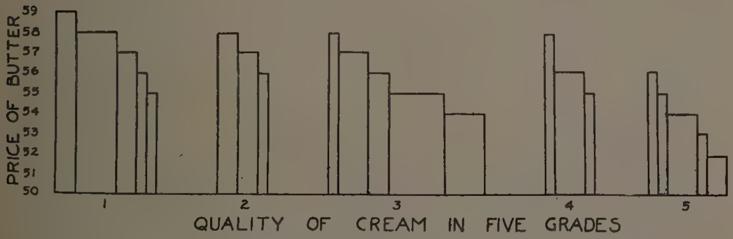

Fig. 10. Range in Prices Received for Butter Made from the Same Grade of Cream

No. 1 or "Good" cream made butter that ranged in price from 55 to 59 cents; and No. 5 or "Sour" cream made butter that ranged from 52 to 57 cents. Thus, although the quality of butter declines with the quality of the cream, there is considerable range in the quality of butter for each grade of cream. (The width of the bars indicates the relative number of creameries.)

One can not know, however, whether the low prices for butter made from poor cream were not partly due to the poor ability of the buttermakers employed in such creameries. The 6 cents is therefore only a rough estimate.

Figure 10 shows, however, that creameries receiving the same grade of cream on the day of the visit did not all receive the same average price for their butter for the year. For example, the 28 receiving "Good" cream received prices ranging from 55 to 59 cents a pound; and the 16 receiving "Sour and Old" cream received prices ranging from 52 to 57 cents a pound. Some of these differences are no doubt due to mistakes in grading cream, or to the fact that the cream delivered on the day of the visit was not a fair sample for the whole year. But making allowance for these possible errors, there is still a range of about 6 cents to be accounted for.

One explanation is the difference in time of year when the butter was sold. Figure 11 gives the monthly range in prices for New York Extras for two four-year periods. Creameries delivering only 51 per cent of their cream in the six summer months, in 1919 received for the same grade of butter 1.7 cents more per pound than those delivering 70 per cent of their cream in the summer. This is a factor in average annual butter prices which is frequently overlooked.

Another cause for differences in butter prices received is freight costs. On a car consisting of 300 tubs of butter (18,900 pounds) the freight cost to New York at present is $364.54; for the same butter

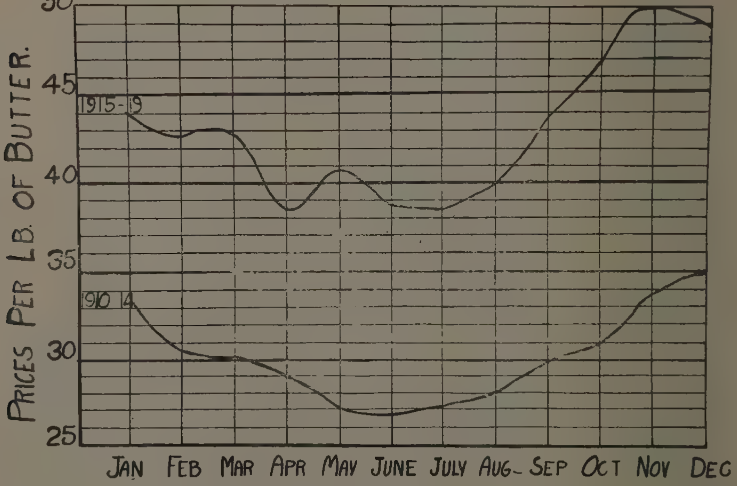

Fig. 11. Monthly Ranges in Prices for New York Extras

Both of these periods are periods of rising prices, but especially the 1915-19 period; hence the December averages are considerably above the January averages.

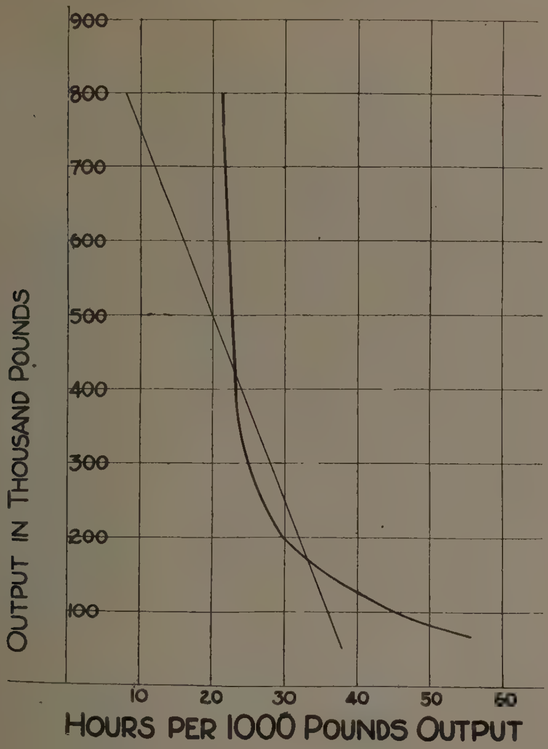

Fig. 12. Relation of Output to Labor and Management Time

For 100,000-pound creameries, the average rate is about 45 hours per thousand; for 500,000-pound creameries, about 23 hours per thousand. The average rate of decrease, indicated by the straight line, is 4.5 hours for each additional 100,000 pounds of output; but the curved line shows that it is very rapid under 200,000 pounds, up to the point where the time of one buttermaker is fully utilized.

Method of using curve.—Locate on the vertical scale the point which represents the output of butter in your creamery. Extend a horizontal line from this point across the diagram till it crosses the curve. Drop a vertical line from this point until it crosses the horizontal line at the bottom of the diagram on which the scale of hours is indicated. The point where the base line is crossed represents the prevailing number of hours per 1000 pounds of output for creameries with your output.

shipped at "less than carload" rates, it is $543.12. This is a difference of not quite a cent a pound (0.94 cent).

Another factor in differences in prices is skill and judgment in choosing a market and a commission firm. These, however, are relatively unimportant. More important are the differences in prices charged patrons for butter, differences in prices at which butter is sold locally, differences in packing the butter, whether in prints or tubs, etc.

There still remains an estimated difference of 2.3 cents of the total range of 10 cents per pound to ascribe to the buttermaker himself and his plant and equipment. As already explained, we can not be sure that some of this is not due to the fact that the poorer buttermakers did not have as good cream to work with as the better buttermakers. Altho we have made an allowance for differences in quality of cream, we may not have allowed for all of it, as some may be so identified with poor buttermaking as not to be apparent. Even if we allow only 2 cents a pound for differences in buttermaking and plant and equipment, it amounts to $2500 for an average output of 125,000 pounds. This point will be discussed later.

Table V can, of course, be only an estimate, because one does not know to what extent the various causes reinforce or run counter to each other.[7] Any one of the causes could reasonably have been as significant as indicated in the first column as "possible range," or less significant than indicated in the second column as "actual range."

Can the range in butter prices be reduced?—The principal factor in quality of cream is the frequency of its delivery. Many farmers in Minnesota can not afford to deliver more frequently—the extra price received for fresher cream will not pay for the extra cost of hauling oftener. This is the case on farms a long way from creameries and with few cows. The condition is prevalent in the Red River Valley, the southwestern corn section and the cut-over section, and on many farms in the intermediate dairy section. Unless the farmers keep more cows, it is foolish in most cases to urge them to deliver more frequently. We can be thankful that they are delivering at all—not long ago they were making butter on the farm and selling their butterfat in that way. In twenty years there has been a decrease from 22 million to 4 million pounds of butter sold from farms in Minnesota.

TABLE V

ESTIMATED RANGE IN AVERAGE ANNUAL RATES RECEIVED FOR BUTTER IN 1919 WHICH WAS DUE TO SEVERAL CAUSES

Causes	Possible range*	Share in actual range†
	Cents	Cents
Quality of cream	6.0	4.0
Skill in buttermaking, and plant equipment	4.0	2.3
Seasonal variations in receipts	2.0	1.7
Marketing methods and costs	3.0	2.0
Total range	15.0	10.0

* This means that if some of the creameries receiving the poorest cream had also the poorest buttermakers and equipment, the most expensive marketing methods, and lowest relative cream receipts in winter; and some of those receiving the best cream had exactly the opposite of the above in all three particulars, the difference in price received for butter would have been 15 cents.

† This means that because some of the creameries with poor cream had fair to good buttermakers, and vice versa, and so for the other three factors, the actual range between highest and lowest was only 10 cents (see Figure 4) excluding irregular cases.

Nor can we urge the farmers in all sections of the state to keep more cows. It is likely that corn, hogs, and beef cattle will always take precedence over dairying in the corn belt and in southwestern Minnesota because the earth has much more potential dairy-farming territory than corn-and-hog territory. This is evidenced by the fact that corn and hog prices have increased more rapidly than butter and cheese prices in the last twenty years. Dairy farming is likely to increase, however, in the small-grain regions north of the corn belt, partly because livestock is needed to improve the farm organization in this territory, partly because the growth of population will call for more dairy products, and partly because there is as much available wheat and oat land in the world as dairy farming land. There is also a twilight zone between the corn belt and the small-grain region where the "corn, hog, and dairy cattle" combination is likely to be further developed, as it has been under similar circumstances in southeastern Wisconsin and northeastern Illinois. Also as the land is gradually cleared in the cut-over section, there will be more cows and more creameries within reach.

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[7] The data were not in such shape in this case as to make possible a multiple correlation analysis.

Therefore there is hope for improvement in the quality of the cream in many parts of Minnesota as time goes on, merely as the result of an increase in dairying and more frequent deliveries.

The quality of the cream can also be improved by better sanitation and more cleanliness in handling the milk and cream, and better care of the cream while it is awaiting delivery. Grading the cream may also prove effective under some circumstances.

The next important way to reduce the range in butter prices is to get better buttermakers. Small weak creameries can not ordinarily hire high-class buttermakers—the larger creameries with better quality of cream outbid them. The trouble is that there are not enough high-class buttermakers to go around. There has already been great improvement, however, and there is sure to be more in the future. The way out is to train more buttermakers; and especially to select more carefully the men who are trained.

Probably a little can be done in improving the quality of the butter by looking after the equipment carefully and keeping it in better condition.

We shall always have seasonal variations in cream receipts because we shall always have differences in systems of farming in Minnesota.

The only other way to reduce the range in butter prices is therefore to standardize marketing practices and price policies. Some things along this line are feasible; for example, combining shipments will equalize freight costs somewhat; but freight costs will always be a little higher in northwestern than in southern Minnesota. Likewise there is no reason why all creameries should have the same price policy for local sales and sales to patrons.

We can conclude, therefore, that the range in price received for butter can be reduced considerably by improving the buttermakers; to some extent by taking better care of the cream; to a greater extent, but more slowly, by improving the quality of the cream along with more dairying and more frequent deliveries; and to some extent by shipping in carload lots. Perhaps the range of 10 cents can in time be reduced to 5 or 6 cents, but it will take a long time to do it—the next ten years may make a difference of 2 or 3 cents.

Range in overrun.—Of the three factors determining the price the farmer receives for his butterfat, overrun is the least important. The ordinary range is from 20 to 26 per cent, but two-thirds comes between 22 and 24 per cent.

The range in overrun is probably due principally to four things: (1) Varying amounts of moisture, salt, and other ingredients in the butter, (2) variations in losses of butterfat in handling and churning, (3) variations in reading the butterfat test of the cream, and (4) variations in weighing the cream when delivered. According to Table VI, under-reading the butterfat test of 30 per cent cream by 0.2 per cent, which is about the average under-reading when readings are in half-per cents and always read down, will increase a "true overrun" of 23 to 23.82 per cent; and under-reading the same cream 0.4 per cent will increase a "true overrun" of 23 to 24.66 per cent.

TABLE VI

EFFECT ON OVERRUN OF UNDER-READING BUTTERFAT TEST OF 30-PER CENT CREAM*

Butterfat reading	Overrun					
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
Correct reading	20.00	21.00	22.00	23.00	24.00	25.00
1 per cent below	20.40	21.40	22.41	23.41	24.41	25.41
2 per cent below	20.80	21.81	22.82	23.82	24.83	25.83
3 per cent below	21.21	22.82	23.23	24.24	25.25	26.26
4 per cent below	21.62	22.63	23.65	24.66	25.67	26.68
5 per cent below	22.03	23.05	24.06	25.09	26.10	27.11

*The method of calculation is as follows: 100 pounds of cream testing 30 per cent will make 36 pounds of butter at 20 per cent overrun. (36 ÷ 30 = 120.) If the test is read 29.9, then the overrun will read 20.40. (36 ÷ 29.9 = 120.40.)

According to Table VII, under-weighing a 5-gallon can of 30 per cent cream by 0.2 pound will increase a true overrun of 24 per cent to 24.62; and an underweighing of 0.4 pound will increase it to 25.25.

Losses in the creamery probably vary from less than one per cent of the butterfat delivered, for very large creameries, to more than 3 per cent for small creameries with careless workmen. Minnesota Bulletin 177 gives 1.4 per cent for the Albert Lea creamery. This is equivalent to an overrun of 1.75. Of this, about one per cent was churn loss and 0.75 mechanical losses in vats, heaters, pasteurizers, etc.

TABLE VII

EFFECT ON OVERRUN OF UNDER-WEIGHING CREAM*

Weighing method	5-gallon unit	8-gallon unit	10 gallon unit
	Per cent	Per cent	Per cent
Correct weight	23.00†	23.00	23.00
0.2 pound below	23.62	23.38	23.31
0.4 pound below	24.24	23.77	23.62

* Assumptions: true overrun of 23 per cent, and cream test of 30 per cent.

† 5 gallons = 40 pounds which at 30 per cent test = 12 pounds of butterfat which at 23 per cent overrun = 14.76 pounds of butter. But 39.8 pounds at 30 per cent test = 11.94 pounds of butterfat. 14.76 ÷ 12 = 123; 14.76 ÷ 11.94 = 123.62.

Minnesota and federal statutes require butter to contain 80 per cent of butterfat, and less than 16 per cent of moisture. Eighty per cent butterfat means an overrun of 25 per cent, counting no mechanical losses. Every creamery would profit if it could exactly attain the 15.9+ per cent of moisture; but this is so difficult as to be impracticable. If the buttermaker aims at 15.5 per cent, the product obtained will probably vary from 15 to 16 per cent, but will practically always be this side the limit. If he aimed at 15.9+ per cent, the product would frequently exceed the limit.

About the same thing is true for salt. A product with more than 3 per cent of salt in it will surely be too salty for most markets; hence it pays better to try for a little less.

If one-half per cent of the possible 16 per cent of moisture is not incorporated in the butter, and only 2.5 per cent of salt, the true overrun, assuming no churn losses and the like, will be 23.75 per cent. Butterfat losses will reduce this probably by 2 per cent. Yet the average overrun of the 301 creameries in Figure 6 was 23.47, and 48 per cent of them had an overrun of more than 23.75.[8] Most of the overruns of more than 23.75 are likely to be due partly or entirely to the under-testing and under-weighing presented above. This is surely true of the overruns of more than 24.50, which include nearly 30 per cent of the 301 creameries. The 140 creameries with overruns of more than 23.75 average 1.05 per cent too high. If creameries with overruns of more than 23.75 per cent under-test and under-weigh, there is no reason for believing that many creameries with overruns of 21 and 22 per cent may not under-test and under-weigh also, this under-testing and under-weighing merely serving to conceal the fact that they are not getting enough moisture or salt into the butter or that they have high churn losses. The under-reading of tests and weights does not really rob the patrons of any of their returns—it merely gives them a higher price per pound of butterfat for proportionately fewer pounds. The real evil involved is that it conceals real losses from moisture deficiencies and handling and churning.

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[8] Average for all creameries in the state in 1920 was 23.14, according to the reports of the State Dairy and Food Department.

Range in creamery costs.—The third factor in range in price paid for butterfat is the cost of manufacturing the butter and preparing it for market. As already stated, the ordinary range in creamery costs is from 2 to 7 cents per pound of butter. Figure 5 shows that nearly two-thirds of the creameries have costs between 2.75 and 4.25 cents, and the remainder are spread out evenly over the rest of the range from 2 to 7 cents. It is the purpose of this bulletin to analyze in detail this range in costs and the reasons for it. This will furnish the basis for an analysis of the economic organization of creameries. For each creamery covered in the survey complete financial records were obtained, as well as estimates of the distribution of time of labor and management. The floor space of each creamery was measured and an inventory taken of the plant and equipment. A cost accounting system for creameries was devised and the data for each of the 88 creameries were put through this system separately. Thus there resulted 88 separate sets of accounts showing 88 separate labor, space, equipment, and other costs per pound of butter; likewise 88 separate receiving, babcock-testing, churning, and other process costs per pound of butter. These costs vary greatly. The variations have been analyzed and the factors responsible for them have been determined wherever possible.[9]

It should be made clear at this point that the purpose of this analysis is not to determine costs. Costs have been introduced merely as a means to the end of discovering economy in creamery organization. Costs in themselves have little value for such a purpose—it is only when they are analyzed in combination with other organization facts that useful conclusions can be derived.

CLASSIFICATION OF COSTS

Table VIII presents the classification of costs used in this analyzis, together with a summary of the results. The costs analyzed are the costs of converting the raw materials (cream and milk) into a finished product packed and ready for the market. No cost of the raw materials is to be considered. What is paid the patrons for butterfat is considered as a result rather than as a cost. A co-operative creamery is an institution for marketing butterfat. It is as successful as the returns to the producers for a given grade of cream are high. While this analysis does not exactly fit the 8 proprietary creameries included in the tables, the error introduced is very slight.

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[9] The method of partial and multiple correlation analysis was used wherever it promised results. The combining of accounting and statistical methods in this way in a cost study promises many valuable results. Only by the survey method is it ordinarily possible to bring together enough cost records at any one time to allow statistical analysis of results, and then the question arises as to whether the survey method does not introduce so many errors in the original data as to vitiate the results. This study throws considerable light on this question. In many ways, creameries lend themselves especially well to such a study. Creamery plants are similar in type and methods. Ordinarily only one product is turned out. Also co-operative creameries, especially, must keep reasonably good records. On many points, however, the data are inadequate or biased. The bias in some cases can be partly eliminated by statistical methods. In other cases, detailed daily cost records will be needed.

The costs are first classified as "Elementary Costs," and finally as "Process Costs."[10] The sum of all elementary costs equals the sum of all process costs. The first classification divides all costs into the elements of production—site, buildings, equipment, labor, management, supplies, and miscellaneous. The second classification principally divides all costs into the following processes: receiving, babcock-testing, preparation for churn, churning, preparation for market, record keeping, and correspondence. Hauling, sidelines, and extra space are really separate from the main and current business of the creamery, and hence are classed as separate costs. Buttermilk and skimmilk disposal should in most creameries be included as one of the regular creamery costs.

Between the elementary and process costs are six intermediate costs. These represent re-combinations of the elementary costs which are themselves distributed to the process costs. Power cost, for example, represents a combination of building, equipment, labor and management, and supplies and miscellaneous costs. It enters as a cost into all the manufacturing costs.

Table VIII also gives the average per creamery and per 1000 pounds of output for each of the elementary, intermediate, and process costs. The purpose of this table is to show the relative importance of the various costs, and for purposes of such a comparison, the average is the most usable index. The averages per 1000 pounds of output are included here merely for economy of space and convenience of reference in later pages. Average costs per unit of output have little significance in themselves—it is variations in cost that are significant, and these will be presented in the pages following.

Of the four elementary costs, Supplies and Miscellaneous is the largest. This is because it includes the large items of coal and electricity, tubs and boxes, ice and salt. Labor and Management costs, representing nearly a third of all creamery costs, will, however, be found to offer the principal reasons for variations in costs.

Of the process costs, preparation for market is high partly because of the cost of tubs and boxes, and partly because of the labor of packing.

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[10] Cost accountants will note that this classification is different from "Prime Costs." The concept of prime costs is based on the technic of cost accounting method and not upon the fundamentals of the economic organization of an enterprise.

TABLE VIII

CLASSIFICATION OF CREAMERY COSTS

Elementary Costs

Item	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Building and site	$1092	11.7	$4.68
Equipment	929	9.9	3.98
Labor and management	3085	32.9	13.21
Supplies and miscellaneous	4267	45.5	18.28
Total	$9373	100.0	$40.15

Intermediate Costs

Item	Per creamery	Per 1000 pounds of butter
Power	$1184	$5.08
Water	145	0.62
Cold storage	599	2.57
Storage of supplies	131	0.56
Cleaning	545	2.34

Process Costs, Etc.

Item	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Process costs			
Receiving	$714	7.7	$3.06
Babcock-testing	482	5.1	2.07
Preparation for churning	1347	14.4	5.76
Churning	1418	15.1	6.07
Preparation for market	3541	37.5	15.06
Record keeping and correspondence	811	8.6	3.48
Buttermilk and skimmilk disposal	13	0.1	0.06
Extra space	127	1.4	0.54
Hauling	25	0.3	0.11
Sidelines	89	0.9	0.38
General maintenance	271	2.9	1.16
General management or overhead	562	6.0	2.40
Total	$9373	100.0	$40.15

Ultimate Costs

All Cost Items

	Cents
Per pound of butter	4.02
Per pound of butterfat	4.96
Excluding Sidelines, Hauling, and Extra Space	
Per pound of butter	3.91
Per pound of butterfat	4.84
	Pounds
Average output of butter	233,304
Average input butterfat	188,963
	Per cent
Average percentage overrun	22.73

In the following analysis, the unit in which costs are expressed is pounds of butter rather than pounds of butterfat. The average cost per pound of butter of the 88 creameries is 4.02 cents; and the average cost per pound of butterfat is 4.96 cents. The relation between these two costs of course depends solely upon the amount of overrun, which in this case is 22.73. Since the overrun is different in different creameries, the relation between costs of butter and butterfat will vary. The range of the 88 creameries will therefore be somewhat different on the two bases.

The reasons for using butter as the unit in place of butterfat are (1) The buttermaker customarily thinks in terms of pounds of butter; (2) most manufacturing plants compute costs in terms of output rather than input; and (3) the errors of under-testing and under-weighing in many creameries make butterfat a less reliable measure than butter. On the other side of the question it may be said (1) that the co-operative principle that such enterprises as creameries are service enterprises which take the farmer's product and process it and dispose of it at cost, would require costs to be figured in terms of the unit in which the farmer sells his product, in this case, butterfat; and (2) that the most important factor in overrun is the amount of moisture and salt added to the butterfat. Thus there are strong arguments on both sides, and for some purposes the results should no doubt be expressed both ways.

ELEMENTARY COSTS

Each of the four elementary costs will now be analyzed separately. Many of the items included in this analysis are based on estimates. None of the results are therefore to be taken as highly accurate. Ordinarily no conclusions will be stated in which the error of estimates makes the results doubtful; or if they are stated, the degree of probable error will be indicated.

LABOR AND MANAGEMENT

Labor and management costs include all salaries and wages paid except for special labor hired for such work as draying, filling the icehouse, painting, repairs to the plant and equipment, and the like. These are included under "Supplies and Miscellaneous."

Later in the bulletin, labor is separated from management, and record-keeping and correspondence are separated from other forms of labor. In this first analysis, however, all are combined.

The employees of a creamery may be classified as in Table IX and Table XIII. In Table XIII each creamery is considered as having one buttermaker or head buttermaker. He is frequently described as "buttermaker-manager" or "operator." These 88 creameries in addition employ 11 men who are designated as managers, 64 full-time helpers (in some cases these are trained or experienced buttermakers), 19 part-time helpers, 67 secretaries, and 7 bookkeepers; 23 have salaried treasurers, and 63 have salaried directors.

The analysis of labor and management costs is taken up in three stages, (A) the time requirement (hour as unit) per 1000 pounds of butter, (B) the rate of pay per unit of time, and (C) the product of A and B, that is, the labor and management cost per 1000 pounds of butter. If it takes 30 hours of labor and management to make 1000 pounds of butter, and the rate of pay is 40 cents per hour, then the labor and management cost is $12.

TABLE IX

HOURS OF LABOR PER YEAR OF YEAR-ROUND CREAMERY EMPLOYEES, BY NUMBER OF HELPERS

Employees	No helper (28)*	One helper (40)*	Two or more helpers (20)*	All creameries (88)*
Buttermakers	3249	3351	3130	3352
Helpers	....	2714	2754	2733
Secretaries	702	1024	1356	997
Bookkeepers	822	1980	1731	1664
Managers	1342	1206	1984	1555
Directors	98	108	180	119
Treasurers	120	173	180	169

* Number of creameries.

Hours.—Table IX shows the average hours per year of the year-round employees. Most of the employees except buttermakers and full-time helpers have other employments. This is true of most of the managers. In this table, the 88 creameries are put into 3 groups according to the number of "helpers" employed. (Creameries with part-time helpers are put in the group into which they fit most nearly.) For full-time employees, the hours are about the same for all groups, but for part-time employees, such as secretaries, directors, and the like, the increase in hours is very marked.

The buttermakers' hours average least in the largest creameries because some of them do not quite need all the helpers they have. In the group of 28 with no helpers, are some creameries so large that one buttermaker must put in very long hours to handle the work, but more which do not keep one buttermaker fully employed, with the result that the hours for such creameries are somewhat below the average.

The ordinary range in buttermakers' hours is from 2900 to 3600 per year, but 20 buttermakers gave estimates of over 3600 hours per year and 10 estimated over 4000 hours per year. The evidence shows that several of these estimates were too high. The error arose from the fact that many buttermakers put in a good share of their working hours in and around the creamery, whether really at work or not, and the tendency is to include all these hours as working time. (The same difficulty is experienced in farm cost accounting.) Only 7 buttermakers worked less than 2700 hours per year.

The ordinary range for full-time helpers is from 2700 to 3300 hours. Table IX, however, includes a large number who were not really employed full-time the year around. Eight worked more than 3300 hours per year.

The salaries per year for full-time men increase somewhat with the hours worked per year, or vice versa. Each $100 additional salary of buttermakers, however, represents an average of only 42 more hours of work per year, a little less than one hour per week. For full-time helpers, there seems to be no relation between hours of work and salary. (In making this analysis all part-time workers were eliminated—of course such workers receive wages in accordance with the time they work.) Buttermakers therefore do not receive appreciably higher salaries merely because they work longer hours. There are special cases, to be sure, in which the work to be done is heavy for one, but not enough for a helper, and a buttermaker is given an extra salary for handling the work alone.

Hours per 1000 pounds of butter.—Table X shows the range in hours per 1000 pounds of butter. The average for the 88 creameries is 30.7 hours, and the ordinary range from 20 to 45 hours. As already explained, this average is somewhat high because of over-estimated hours; the error, however, is surely less than two hours per 1000 pounds and probably less than one hour.

TABLE X

RANGE IN HOURS OF LABOR AND MANAGEMENT PER 1000 POUNDS OF BUTTER

Hours per 1000 pounds of butter	No. of creameries in group	Average of group
		Hours
Under 20	8	17.0
20 to 25	21	22.7
25 to 30	18	27.3
30 to 35	15	32.3
35 to 45	13	38.8
Over 45	12	51.5
All creameries	88	30.7

Figure 12 shows, however, that the hours per 1000 pounds of butter decrease markedly with output. In general, every 100,000 pounds of output is accompanied by an average decrease of 4.5 hours of labor and management per 1000 pounds of butter. This average is expressed by the straight line. But an average line does not fit the facts very well, as the decrease is very slight, being for creameries between 400,000 and 800,000 pounds of output at the rate of only 0.3 hour per 100,000 pounds. But between 50,000 and 150,000 pounds, the decrease is at the rate of 60 hours per 100,000 pounds. Thus a curved line bending sharply around 200,000 pounds of output describes much more accurately than the straight line the relation between output and time requirement of labor and management. The manager of any creamery can determine from this curved line what his hours per 1000 pounds of output should be, unless there are some other causes operating.

The reason for the very slight saving in labor and management with increase in output after from 300,000 to 400,000 pounds is reached, is partly that cheaper help, working less rapidly, is hired for some of the ordinary work, such as packing butter and cleaning, and partly that from this point on nearly all operations are performed with a full load, and increasing output simply increases by so much the scope and number of operations. Under 300,000 pounds, churns, ripeners, power plants, etc., are run at less than full capacity, yet require about as much time as they would if run at full capacity. In the smallest creameries, even the buttermaker has to put in much time when he is not fully occupied.

Seasonality of milk flow.—The receipts of the heaviest month of the year determine in many cases the amount of help hired, for it is not always practicable to hire extra labor for part of the year. Only 19 of 88 creameries employ part-time help (other than for management, bookkeeping, and the like). One would expect, therefore, to find the creameries with heavy summer receipts and light winter receipts using more labor. The 15 creameries receiving over 12 per cent more milk in the heavy months of the year than in the light months, after allowance was made for difference in output, used two hours more of labor for each 1000 pounds of butter than the 12 creameries receiving less than 7 per cent more butter in the heavy than in the light months. This is a difference of more than 6 per cent.

Convenience of arrangement.—At the time of the survey, the creameries were roughly classified into three groups as to convenience of arrangement. Table XI shows the results of this classification. At 42 cents per hour, the conveniently arranged creameries saved $2.23 per 1000 pounds of butter, or $445 for a 200,000-pound creamery, over the very inconveniently arranged creameries.

TABLE XI

Relation of Convenience of Arrangement to Labor

Arrangement	No. in group	Hours per 1000 lbs.*
Convenient	15	28.7
Somewhat inconvenient	55	30.4
Very inconvenient	21	34.0
All creameries	88	30.7

* After allowance was made for differences in output.

Rates per hour.—The rate per hour for each employee was obtained by dividing annual salary by hours per year; and average rates per hour for each creamery by dividing the annual payroll (excluding salaries of treasurers and directors) by total hours of labor and management per year.[11] Table IX gives hours per year for different classes of employees. Table XII gives annual salaries by classes of employees; Table XIII, by classes of employees in different combinations; and Table XIV, the rates per hour in the different combinations. The salaries of buttermakers increase with the size of the labor force and output of creameries for all groups with enough creameries to give a good average. For the 8 creameries with no helper, the average is $1669; for 13, each with a part-time helper, $1742; for 22, each with a full-time helper, $1726;[12] for 8, each with two full-time helpers, $1806. All but 19 of the buttermakers covered in the survey received salaries between $1400 and $2100. The lowest salary for the buttermaker was $1000; and the highest was $4000. Nine received salaries under $1400, and 10 salaries over $2100. Between $1400 and $2100 the distribution is very even, 9 receiving from $1400 to $1500, and 9 from $2000 to $2100, and about the same number for each wage interval between. Managers' salaries are very erratic, ranging from $1300 to $1600 for several part-time men, to $4000 for one full-time man. Several others were over $2100.

Where managers are full-time men, either doing little but look after the business details, as in the very large creameries, or combining this with buttermaking, their salaries are larger than those of buttermakers. In such cases buttermarkers' salaries are likely to be reduced, sometimes to the level of experienced helpers.

Salaries of first helpers also increase consistently from $742 for one helper with no secretary to $908 for one helper with a secretary, and $1185 for two helpers with a secretary. In the largest creameries the second helper draws as large a salary as the first helper. Salaries of secretaries and bookkeepers likewise increase regularly. Most of the salaries of helpers are between $700 and $1200, only 6 receiving

[11] If the question of cost by seasons was involved, or of different products using labor at different seasons, this method would be objectionable, for some of the labor and equipment of a creamery is required mostly for the early summer months of heavy receipts. However, there is no question of alternatives here, for a creamery has no choice except to take the cream when it comes.

There is, however, one serious objection to this method, namely, that it does not give a correct distribution of labor and management costs to different processes. In large creameries, men of different degrees of skill and experience are employed at different rates to do the receiving, churning, cleaning, packing of butter, record-keeping, etc.; in the smaller creameries, one man may do all of these at one contract rate. The salary rate in such a case is really a combination of rates for different tasks; but it does not appear so in the contract, and there is no very satisfactory way of making the separation.

[12] In many cases the helper is really a second buttermaker, in which case both receive about the same salary.

more than $1200, and 7 less than $700. Those receiving $1200 and more of course have had experience or training as buttermakers, or both. Those receiving the lowest salaries are either boys or, in a few cases, part-time helpers.

These are the salaries prevailing in 1919. There has been both an increase and a decrease in the salary level since then.

Reduced to rates per hour, buttermakers' earnings do not increase in general with the size of the creamery—longer hours in the larger creameries apparently offset the slight increase in salary. The ordinary range is between 40 and 70 cents an hour, and the extreme range 30 and 92 cents an hour. Ten are receiving less than 40 cents an hour, and 13 over 70 cents an hour.

TABLE XII

AVERAGE ANNUAL SALARY AND FORMS IN WHICH IT IS RECEIVED

Employing	No. of creameries employing	Cash salary	Perquisites	Total
Buttermaker	88	$1634	$115	$1749
Helpers (full time)	60	991	...	991
Helpers (part time)	24	98*	...	98*
Secretaries	66	357	3	360
Bookkeepers	16	662	...	662
Managers	18	1420	40	1450

* Per month.

First helpers' salaries average 31.2 cents per hour as compared with 54 cents for buttermaker-operators. It will be noted that when second helpers are employed, the first helpers receive considerably higher pay than when only one helper is employed. The rates for first helpers increase as the size of the business increases, from 23.7 cents an hour to 28 cents, then to 34.5 cents when a second helper is taken on, and finally to 46.8 cents when a third helper is taken on. The rate when one helper alone is employed averages 27.6 cents an hour. If second helpers where two are employed and third helpers where three or more are employed are averaged with these, the rate is 28.3 cents an hour. The average of rates for first helpers when a second helper is employed combined with rates for second helpers when three or more are employed, is 36.7 cents an hour. Averaged on this basis, which more nearly represents the facts, the rates range as follows: 46.8, 36.7, and 28.3 cents. The ordinary range in helpers' salaries is from 25 to 40 cents an hour, but 8 receive less than 25 cents per hour.

Bookkeepers are paid higher rates when they do the secretary's work than when a secretary is employed in addition. However, in the case of the 8 creameries having both bookkeepers and secretaries, 4 listed as secretaries are also bookkeepers, and those listed as bookkeepers are really bookkeepers' assistants. The average rate for bookkeepers, 51.6

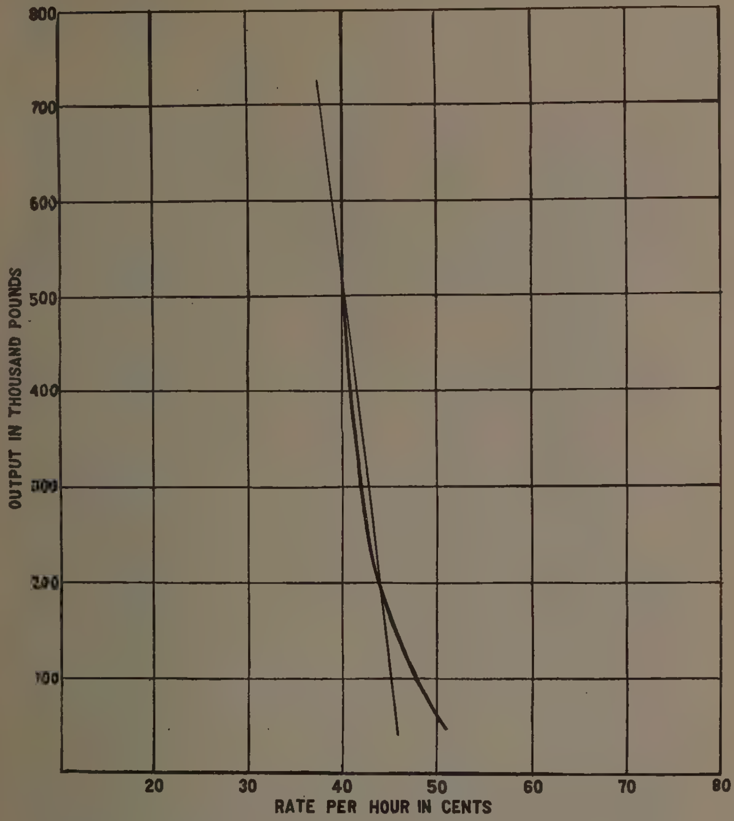

Fig. 13. Relation of Output to Rate per Hour for Labor and Management

The average rate per hour is about 48 cents for 100,000-pound creameries, and about 40 cents for 50,000-pound creameries. The average rate of decrease, indicated by the straight line, is 1.2 cents per hour for each additional 100,000 pounds of output. The actual decrease, however, is according to the curved line, and much more rapid under 250,000 pounds than above this point.

cents per hour, is therefore too low (probably 2 cents), and the average rates for secretaries, 46.8 cents per hour, is too high (probably 0.6 cent). Buttermakers and bookkeepers are therefore paid at about the same rate, and secretaries at a somewhat lower rate.

TABLE XIII

SALARIES OF CREAMERY EMPLOYEES IN VARIOUS COMBINATIONS (Blanks indicate none employed.)

Average ouput in pounds of butter	No. in group	Average annual payroll											Cost per pound of butter
		Total	Buttermakers	Managers	Secretaries	Bookkeepers	First helper—full time	Second helpers-full time	Others—full time	Part-time helpers*	Directors*	Treasurers*	
													Cents
87,638	5	$1679	$1679	....	....	....	....	....	...	...	...	...	1.92
133,280	16	1974	1669	....	$219	....	....	....	...	...	$70	$16	1.48
140,826	3	2774	2230	....	....	....	....	....	...	$486(4)†	56	...	1.97
146,554	3	2812	1872	....	....	....	$742	....	...	...	135	43	1.92
148,004	4	3040	1739	$1202	....	....	....	....	...	...	72	27	2.05
177,562	13	2614	1742	....	305	....	....	....	...	516(13)†	62	18	1.47
181,637	3	2702	2130	....	212	$273‡	....	....	...	...	50	37	1.49
256,525	22	3147	1726	....	411	....	908	....	...	...	76	26	1.23
326,000	1	4948	1754	1564	....	....	1500	....	...	...	130	...	1.52
177,661	1	4574	2050	....	....	600	1200	....	...	500(1)†	224	...	2.57
383,140	8	4495	1806	....	506§	....	1185	$877	...	...	60	37	1.17
475,514	3	4863	1497	1738	539	....	789	....	...	...	152	148	1.02
623,250‖	5	7639	1635	1187¶(3)†	800(2)†	1050(3)†	1191	1118	$903(9)†	367(1)†	147	112	1.22

* Calculated as the amount paid per creamery for part-time helpers, directors, treasurers.

† Numbers in parentheses indicate number employed in the given group of creameries.

‡ One of these also calls himself a manager.

§ Two of these are classed as bookkeepers, and in two cases the salary is divided between a bookkeeper and a secretary.

‖ Of these 5 creameries, 3 had managers, 2 had secretaries, 3 had bookkeepers, and 4 had 10 extra helpers in all, one being employed part time.

¶ Two of these managers worked on a part-time basis.

TABLE XIV

Rates per Hour of Creamery Employees Under Different Combinations

Average pounds of butter made	No. of creameries	Average rate per hour									
		Operator	Manager	Secretary	Bookkeeper	First helper	Second helper	Third helper	Part time helpers		
									6 months	4 months	3 months
		Cents	Cents	Cents	Cents	Cents	Cents	Cents	Cents	Cents	Cents
87,638	5	55.4	...	...	...	...	...	...	...	...	...
132,280	16	54.0	...	4.74	...	...	...	...	...	...	...
146,554	3	51.2	...	...	...	23.7	...	...	...	...	...
148,004	4	53.6	48.3	...	...	...	...	...	...	...	...
140,826	3	58.1	...	...	...	...	...	...	41.9	26.1	...
177,562	13	52.0	...	42.1	...	...	...	...	25.1	20.8	18.9
181,637	3	54.6	...	...	58.6	...	...	...	...	...	...
256,525	22	56.0	...	48.5	...	28.0	...	...	...	...	...
326,000	1	58.0	107.9	...	...	48.6	...	...	...	...	...
177,661	1	55.0	...	...	...	32.1	...	...	26.8	...	...
335,246	8	51.9	...	50.0	34.4	34.5	27.8	...	...	...	...
475,514	3	48.6	85.8	44.9	...	25.6	...	...	...	...	...
623,289	5	57.8	40.3	46.3	54.3	46.8	40.3	30.5	23.7	...	...
Average all creameries		54.0	58.5	46.8	51.6	31.2	32.6	30.5	27.6	22.6	18.9

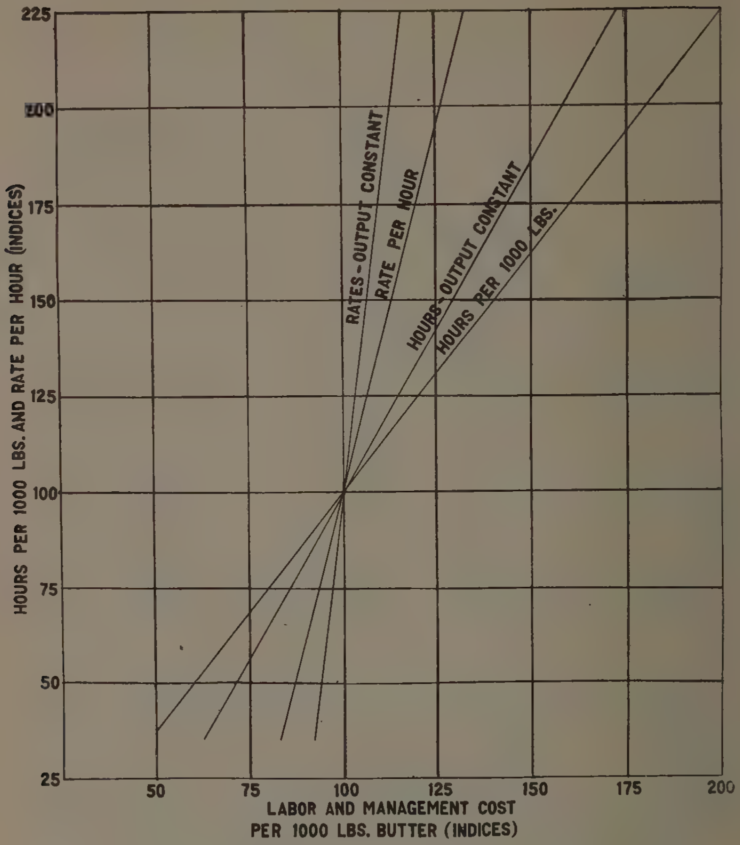

Fig. 14. Relation of Hours and Rate per Hour to Labor and Management Cost

In this diagram rates per hour have been reduced to percentages or indices of the average rate per hour; and similarly hours per thousand, to percentages of average hours per thousand; and the same for labor and management cost per thousand. Only in this way can the effects of rates per hour and hours per thousand be compared. Taking creameries as they are, it appears that rates per hour 50 per cent above the average are accompanied by a 13 per cent higher labor and management cost; whereas hours per thousand 50 per cent above the average are accompanied by a 40 per cent higher labor and management cost. The other set of lines shows that if creameries all had the same output, the effects would be much less pronounced.

The rate given for managers, 58.5 cents, is not an average for real managers, it includes the rates for men bearing that title whose services are of a very miscellaneous nature. And where the manager has this work as a sort of avocation, he may put in time out of all proportion to his salary. The range is from 32 cents an hour to $1.08.

Table XV gives the range in rate per hour by creameries. It is as much due to averaging salaries of high- and low-priced employees in one creamery as it is to difference in salary levels in different creameries. Table VII shows this conclusively—in the creameries with two or more helpers, the average rate per hour is 40.7 cents as compared with 49.9 cents in the creameries with no helpers. Thus one of the economies of larger output is that it permits division of labor and hiring of cheaper help for the work requiring less skill. The same result appears in Figure 13. The straight line, which represents the average for all outputs, indicates a decrease of 1.2 cents per hour for each 100,000 pounds increase in output. According to this ratio, 500,000-pound creameries would be hiring labor 5 cents less per hour than 100,000-pound creameries. The curved line, however, which fits the facts better than the straight line, indicates that for creameries under 250,000 pounds, the rates increase rather rapidly with decrease in output.

TABLE XV

Range in Rates per Hour for Labor and Management by Creameries

Groups	No. in group	Average rate for group
Cents		Cents
Under 30	9	27.9
30 to 35	6	32.6
35 to 40	14	37.8
40 to 45	24	42.3
45 to 50	11	47.3
50 to 55	8	52.2
55 to 60	7	56.3
Over 60	9	66.7
All creameries	88	43.1

By using this curve in the manner previously explained, any manager can determine what average rate per hour he should be paying for labor for a creamery with his output, other things being the same.[13] If his labor is costing him at a higher rate, he will find in many cases that he is using too high a proportion of the higher-class labor. Of course, as will be indicated later, he may be getting a quality of product which more than makes up for the extra cost per hour.

As already explained, rates per hour do not increase quite in proportion to salaries, as the more highly paid men work 42 more hours per year for each addditional $100 of salary. This means that employees receiving $2000 for a year's work, on the average work 210 more hours than employees of the same type receiving $1500 per year.

Labor and management cost per pound of butter.—Table XVI shows the range in cost of labor and management per 1000 pounds of butter. The extreme range, not shown in the table, is from $8 to $31. The average is $13.20. As already explained, labor and management cost per 1000 pounds of butter is the product of the number of hours multiplied by the rate per hour. It varies, therefore, with both these factors. Figure 14 shows these variations graphically.

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[13] Assuming the same salary level as in 1919.

TABLE XVI

RANGE IN LABOR AND MANAGEMENT COST PER 1000 POUNDS OF BUTTER

Groups	No. in group	Average for group
Under $10	12	$8.80
$10 to 13	29	11.60
13 to 16	19	14.30
16 to 19	10	17.10
19 to 22	8	20.50
Over 22	10	27.50
All creameries	88	$13.21

After correction was made for the errors of overestimates,[14] it was found that a difference of 10 per cent in the rate per hour, other things being the same, is accompanied by a difference of only 2 per cent in labor and management cost; while a difference of 10 per cent in number of hours is accompanied by a difference of 18 per cent in labor and management cost. This is indicated in the diagram by the greater slope of the line for hours per 1000 pounds of butter. Reduced to a unit basis, a difference of 10 cents per hour, other things being the same, accompanies a difference of only 62 cents per 1000 pounds, and a difference of 10 hours per 1000 pounds of butter accompanies a difference of $3.45 per 1000 pounds. This can only mean that the higher rates of pay, for various reasons, are accompanied by fewer hours per 1000 pounds of butter, and conversely, the more hours by lower rates of pay. This is evident from Figure 15, which shows that especially the creameries with average rates under 50 cents per hour, average more hours per 1000 pounds of output. This must be due to the greater capacity and efficiency of the more highly paid workmen.

The most important of the other things not the same is output. If creameries were all of the same size, the results would be less pronounced, for as already pointed out (Figures 12 and 13), the creameries with the lowest number of hours per unit of output are likely to be the largest ones, and these also have the lowest rates per hour. Figure 14 shows how much less the effect of the number of hours and rates per hour would be if the creameries were all of the same size.

Figure 16 shows the variations in labor and management cost with output, the heavy straight line expressing the average relation between them, and the curved line the particular relation for any given output. Other things being the same, labor and management costs per unit of output for a creamery of any given output should be as indicated by the curved line. The cost per unit decreases very little above 300,000 pounds. On the average, 100,000 pounds of additional output accompanies labor and management costs lower by $2.24 per 1000

[14] The error of overestimate, as near as could be determined, represented an understatement of 2.05 cents in the rate per hour for each 100 hours cverstatement of hours.

pounds. A little of this decrease is due to the lower rates per hour of the large creameries—if rates per hour were the same, the decrease would be $2.06 per thousand instead of $2.24. If, however, hours per thousand were the same for all outputs, the decrease would be only $1.33 in place of $2.24. The lighter lines in Figure 16 illustrate this.

Table XIII gives average labor and management cost according to the different combinations of employees. An economical combination is the buttermaker-manager, secretary, and two full-time helpers. This gives the 8 creameries an average cost of $11.70 per 1000 pounds of butter. Another economical combination is buttermaker-manager, secretary, and one full-time helper, at $12.30 per 1000 pounds of butter for the 22 creameries. The 13 creameries with part-time helpers made 44,280 pounds more butter per year than the 16 with no helpers, but the payroll cost was $640 more per year, which was almost proportional to the increase in butter output, resulting in costs of $14.70 as compared to $14.80 per 1000 pounds. The creameries with neither helpers nor

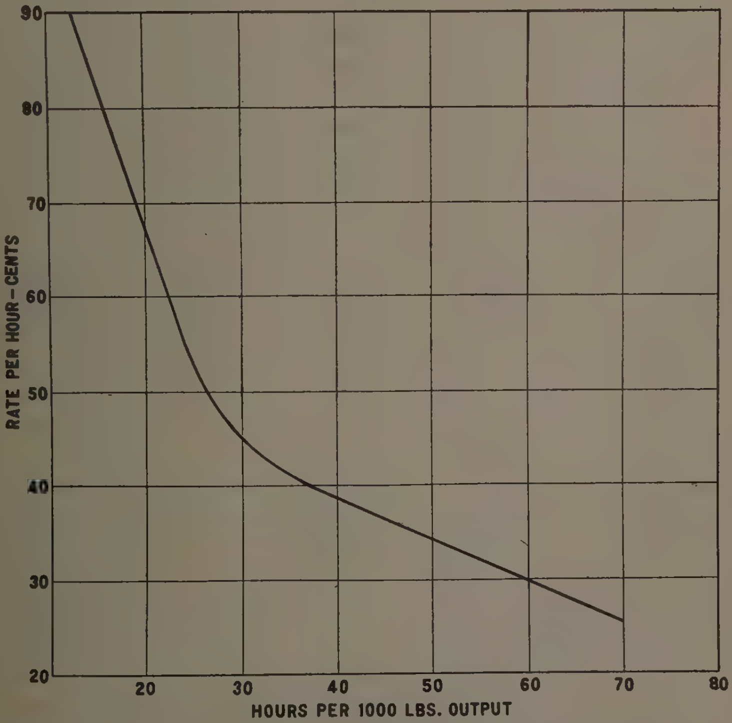

Fig. 15. Relation of Rates per Hour to Labor and Management

The low rates per hour are accompanied by a high number of hours per thousand pounds of output. The low rates arise from putting in long hours to poor advantage, and from the low salaries paid inexperienced slow workers.

secretaries had a labor and management cost of $19.20 per 1000 pounds of butter. This is because of the small output of butter.

The creameries with managers have high labor and management costs per pound of butter if the creameries are relatively small. This is because the creamery has two highly paid employees. The 3 creameries, however, making an average of 475,000 pounds of butter and having both buttermaker and manager, have the lowest cost of any. This arrangement is very similar to a buttermaker-manager and two full-time helpers, and the costs are about the same. The buttermaker in one case is about the same as the first helper in the other case, and receives very little more salary. Such creameries are really large enough to have managers.

Separation of labor and management cost.—Table XVII shows the distribution of labor and management cost between labor, record keeping and correspondence, and management. The term "labor" as here used refers to the labor, mostly manual, of receiving, churning, and the like.[15] The proportion of management cost increases as more help is taken on, and the proportion of labor cost decreases. Part of the reason for the increase in the proportion of management cost is higher rates of pay, and for the decrease in the proportion of labor cost is lower average rates of pay, because part of the labor is low-priced. The percentage of total hours devoted to labor is only one half per cent less for creameries with two or more helpers than for creameries with no helpers. The percentage of total hours devoted to record keeping and correspondence decreases with output, but the rates are somewhat higher. Reduced to a unit basis, the lower the labor and management cost per pound of butter, the smaller the proportion of it which is labor, and the more of it which is management and record keeping and correspondence. This is because the larger creameries have lower costs and more management.

The separating of the three classes of work in a creamery was of course difficult. In only the largest creameries are managers hired to do managing only. The buttermaker-manager does much of his managing incidentally; he makes his plans while he is packing butter or figuring over his accounts. Management is directing other men at labor. As a part of this, or necessary to it, is included organizing the business, laying out the work, buying and selling, hiring, borrowing money, negotiating with patrons, travel, correspondence, and the interpretation of records and study of conditions necessary to the foregoing.

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[15] The only excuse for using the term "labor" here is the want of a better one.

TABLE XVII

DIVISION OF COST BETWEEN DIFFERENT TYPES OF WORK IN CREAMERIES OF DIFFERENT CLASSES

	No helpers		One helper		Two or more helpers		All creameries	
	Average cost	Per cent	Average cost	Per cent	Average cost	Per cent	Average cost	Per cent
Labor	$1481	75.9	$2165	73.2	$3500	71.0	$2150	73.0
Record keeping and correspondence	348	17.8	556	18.8	932	18.9	575	18.6
Management	123	6.3	237	8.0	499	10.1	260	8.4
Total	$1952	100.0	$2958	100.0	$4931	100.0	$3085	100.0

Time spent by the manager in actual correspondence and record keeping, however, was separated out. Record keeping was defined to include the bookkeeping and work upon the records. The recording of weights, tests, and the like was counted as labor at the various processes.

Labor, according to Table XXII, represents 73 per cent of the labor and management cost, record keeping and correspondence 18.6 per cent, and management 8.4 per cent.

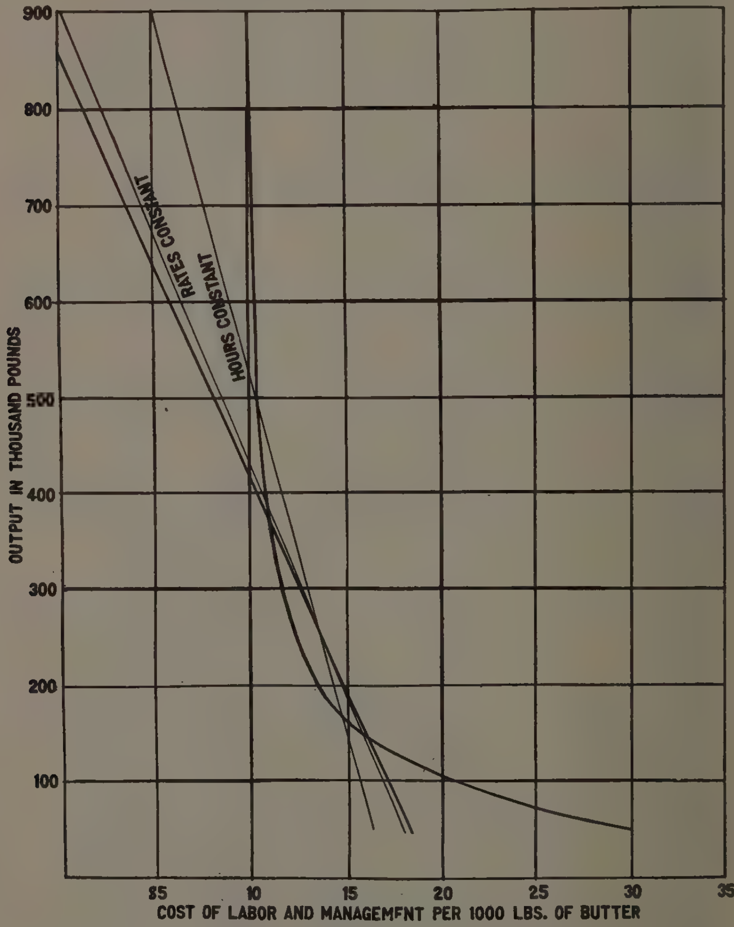

Fig. 16. Relation of Output to Labor and Management Cost

These curves should be read exactly as explained for Fig. 14. The cost per thousand for 100,000-pound creameries averages $21; for 300,000-pound creameries, $12, that is, reading from the curved line. The straight lines express the average effect of output on cost. If the larger creameries paid as high rates as the smaller creameries, the effect of output would be somewhat less; and if they used the same number of hours per thousand, it would be a great deal less.

When labor is analyzed in detail, as were labor and management combined in the preceding pages, labor costs vary with output at the average rate of $2.04 per 100,000 pounds of output in place of $2.24 for labor and management combined; with each ten cents additional rate per hour at the rate of 86 cents per 1000 pounds of butter, in place of 62 cents for labor and management combined; and with each ten hours additional per 1000 pounds of butter at the rate of $4.30 in place of $3.45 for labor and management combined. Table XVIII shows that the labor cost per 1000 pounds of butter is $9.60, representing 22.9 hours at 42.1 cents per hour.

TABLE XVIII

RANGE IN LABOR COST PER 1000 POUNDS AND RELATION TO OTHER COST FACTORS

Groups	No. in group	Average for group	Labor per 1000 lbs.	Labor cost per hour	Output
			Hours	Cents	Lbs.
Under $7.50	16	$6.40	16.6	38.5	429,403
$7.50 to 9.00	15	8.30	19.5	42.7	269,917
9.00 to 10.50	20	9.50	23.7	40.2	211,591
10.50 to 12.50	12	11.20	24.9	45.0	192,517
12.50 to 14.00	6	13.10	28.5	46.1	128,567
Over 14.00	19	19.10	43.3	44.0	118,431
All creameries	88	$9.60	22.9	42.1	233,304

This means that a 10 per cent higher labor rate in the various creameries, taking other conditions as they are, is accompanied by a 3.8 per cent higher labor cost; and 10 per cent more labor hours by 10.2 per cent higher labor cost. Table XVIII gives the ordinary range in labor costs.

Table XIX shows that when the creameries are grouped according to the number of helpers, the hours per 1000 pounds output are nearly the same, but that the rates are much lower for the creameries with helpers.

TABLE XIX

LABOR PER CREAMERY CLASSIFIED ACCORDING TO NUMBER OF HELPERS

	No. of helpers (28)*	One helper (40)	Two or more helpers (20)	All creameries (88)
Output, pounds	125,898	225,077	400,231	233,305
Labor hours	2830	5384	8800	5348
Labor cost	$1481	$2165	$3500	$2250
Labor cost per 1000 pounds of butter	$11.80	$9.60	$8.70	$9.60
Labor hours per 1000 pounds of butter	22.5	23.9	22.0	22.9
Labor cost per hour, cents	52.3	40.2	39.8	42.1

* Number of creameries.

To the above management cost must be added the salaries paid to directors and treasurers, averaging $89 per creamery for the 88 creameries, as indicated in Table XX. Only 23 of the 88 paid salaries to their treasurers, and only 63 to their directors.

TABLE XX

SALARIES OF TREASURERS AND DIRECTORS

	No helpers		One helper		Two or more helpers		All	
	No. of creameries	Salary paid	No. of creameries	Salaries paid	No. of creameries	Salaries paid	No. of creameries	Salaries paid
Number paying salary to treasurer	6	$300	13	$1073	4	$679	23	$2072
Average per treasurer receiving salary	..	50	..	83	..	175	..	90
Number of creameries paying directors	27	2386	28	3238	8	1144	63	5768
Average per creamery paying salaries to directors	..	88	..	116	..	143	..	107

Table XXI shows the increase in payroll, including salaries of treasurers and directors for the 88 creameries, according to output. This table should be useful in determining the reasonableness of the payroll for any size of creamery. It must be remembered that this payroll is on a 1919 basis. Table XXII also shows the direct distribution of labor cost to intermediate and process accounts. The labor element in power, general maintenance, and cleaning is later redistributed to receiving, testing, and the other final process accounts, so that the total labor element in these final process accounts is greater than here indicated.

TABLE XXI

Relation of Payroll to Output

Butter output	No. in group	Total payroll	Butter output	Payroll per 1000 pounds
Pounds			Pounds	
Under 100,000	10	$1976	73,788	$26.78
100,000 to 150,000	19	2371	127,353	18.62
150,000 to 200,000	17	2748	184,394	14.90
200,000 to 250,000	15	2889	215,224	13.42
250,000 to 300,000	10	3503	274,471	12.76
300,000 to 400,000	5	4018	331,792	12.11
400,000 and over	12	5862	541,543	10.82
All creameries	88	$3186	233,304	$13.65

TABLE XXII

Distribution of Labor and Management Cost

Accounts to which distributed	Per creamery			
	Amount		Per cent of total	
Labor		$2250		73.0
Power	$176		5.7	
General maintenance	50		1.6	
Receiving	427		13.9	
Testing	278		9.0	
Preparation for churn	156		5.0	
Churning	307		9.9	
Preparation for market	464		15.0	
Cleaning	348		11.4	
Sidelines	43		1.4	
Record keeping and correspondence		575		18.6
Management (overhead)		260		8.4
Total		$3085		100.0

SPACE COST

Space cost includes building cost and site cost. Together, these constitute 11.7 per cent of the total cost of operating creameries. Building cost is 93 per cent of the total. Building cost and site will be discussed separately and then combined.

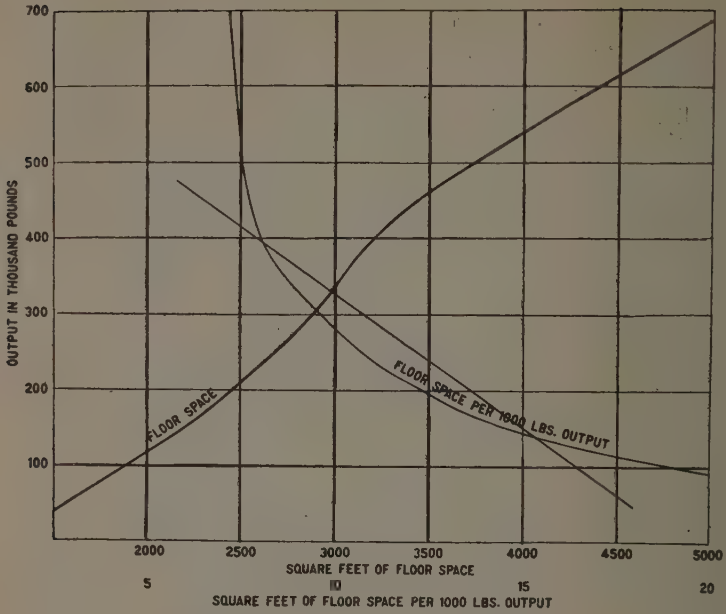

Fig. 17. Relation of Output to Floor Space

Building cost per 1000 pounds of butter may be considered as the product of the number of square feet of floor space times the annual cost per square foot of this floor space. Site cost can be similarly reckoned as ground space instead of floor space; however, in reducing site cost to a cost basis, it was calculated on a floor space basis so that it could be combined with building cost.

Floor space.—The ordinary range in floor space as given in Table XXIII is from 1500 to 3500 square feet. Only 7 out of 88 were over 3500 square feet. The largest creamery included in the survey had 5493 square feet of floor space and the smallest, 705 square feet. Figure 17 shows the relation of output to floor space. For the group of creameries with outputs between 250,000 and 400,000, there is a relatively smaller increase in floor space with output. This is because of the bunching at this point of quite a number of creameries that are running at or above full capacity. Above this point is an increasing number of new creameries built larger than needed at present.

The curve in Figure 17 can not be used as an altogether safe guide as to the size of creamery needed for a given output, because there are more creameries running either over or under capacity at different points on the curve. In general, however, it indicates that floor space increases with output at the rate of about 450 square feet for each 100,000 pounds of output, starting from 1900 square feet for 100,000 pounds.

The other curve in Figure 17 expresses the same relation in terms of floor space for 1000 pounds. It shows that the efficiency of use of space increases rapidly only up to about 300,000 pounds. One important reason, however, that efficiency does not increase more rapidly with the larger outputs is that there are more oversize creameries in these groups. The three creameries with floor space of over 4000 square feet have a very high degree of utilization.

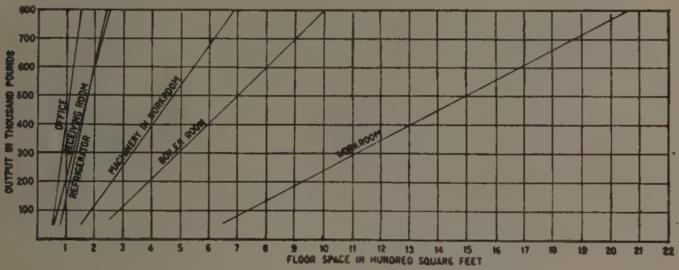

Fig. 18. Floor Space by Departments and Output

Figure 18 shows the division of floor space between departments of the plant for creameries of different outputs. Table XXIV gives the average for 65 creameries, and also readings from Figure 18 for creameries of 100,000, 300,000, and 500,000 pounds. Similar readings for any other output can be made from the diagram. Space for the storage of ice and supplies has been omitted because many creameries have neither, or perhaps store their supplies upstairs.

The figures for boiler-room space combine creameries using and those not using electric power. As will appear later, creameries with electric power average only 35 square feet less floor space than those using no electric power. It is likely, however, that if creameries built in the first place to use electric power could have been segregated, there would have been a greater difference. As it is, boiler-room floor space varies greatly between creameries from 10 per cent to over 23 per cent of the total floor space. The proportion of the total floor space is larger in the smaller creameries than in the larger ones.

TABLE XXIII

Range in Floor Space of 88 Minnesota Creameries

Floor space	No. of creameries	Butter output in 1919
Sq. ft.		Lbs.
Less than 1500	6	149,900
1500 to 2000	17	152,700
2000 to 2500	22	229,700
2500 to 3000	25	262,500
3000 to 3500	12	292,800
3500 and over	6	302,500

TABLE XXIV

Floor Space for Creameries of Various Sizes, Square Feet*

Output	Office	Receiving room	Refrigerator	Boiler room	Machinery work room	Work-room space
Lbs.						
100,000	55	70	90	285	185	740
300,000	85	120	135	495	320	1060
500,000	115	170	170	700	430	1500
Average of 65 creameries	75	95	120	410	280	930

* Not including space for storage of ice and of supplies.

Office space is also very irregular. For example, the office floor space for the creameries with outputs between 400,000 and 500,000 varies from 30 to 300 square feet. The proportion of office space increases with the larger creameries. This is because the larger creameries are likely to have more business in proportion to their output than the smaller ones.

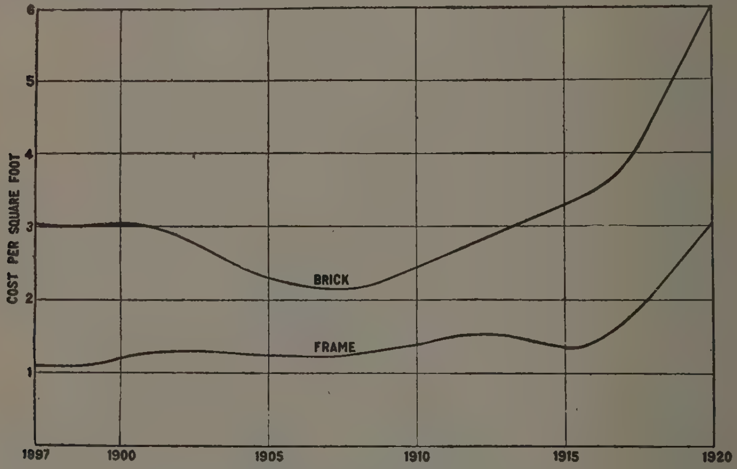

Fig. 19. Building Cost per Square Foot, 1897 to 1920

The data are based on the buildings actually erected in these years combined with the Bureau of Labor data on the costs of building materials and labor. They are, of course, only approximations.

The proportion of space actually occupied by machinery decreases with output; a creamery with 500,000 pounds output has about two per cent less of its total space actually occupied by machinery than a 100,000-pound creamery. The proportion of space in the workroom, however, increases with the size of the building. This can only mean more work space around equipment, more passageway or more extra space. The proportion of refrigerator space decreases slightly with output, but this is partly because more of the larger creameries are using ice machines.

There is clear evidence that much space is wasted in many creameries in departments of the plant which are larger than need be. On the other hand, many plants have departments which are cramped for room merely because of poor planning.

Convenience of management of the plant is also a factor in utilization of space. In the more convenient plants, less space is wasted in passageways and in work space around machinery. A group of 22 creameries indicated as "inconvenient," after making allowance for difference in output, used 1.8 more square feet per 1000 pounds of butter than the group of 16 "convenient" creameries. This 1.8 square feet is 16.5 per cent of the average.

One important factor in floor space and cost is extra space for expansion of business. It was difficult to determine this, because what might be extra space is frequently used up by leaving more space around the equipment. Only when unused space was unoccupied was it counted. On this basis, 56 of the 88 creameries had extra space as indicated in Table XXV. This extra space makes the relation between output and floor space somewhat irregular.

TABLE XXV

Extra Space for Expansion, Square Feet

Groups	No. in group	Average for group		Average cost	
		Per creamery	Per 1000 pounds butter	Per creamery	Per 1000 pounds butter
Sq. ft.					
Less than 100	16	68	0.33	$39	$0.19
100 to 200	19	151	0.19	98	0.32
200 to 300	12	255	1.34	108	0.57
300 to 400	5	358	1.96	192	1.05
400 to 500	..	...	...	...	...
Over 500	4	820	1.95	625	1.49
All creameries	56	216	0.88	$127	$0.52

Other factors affecting the utilization of space are seasonality of milk receipts, efficiency of labor and management, and proportion of butterfat received as milk and cream. The creameries receiving over 11 per cent more of their annual milk supply during their heaviest month than during their lightest month, after full allowance was made for difference in output, used on the average 5.5 more square feet per 1000 pounds of butter than the creameries receiving less than 8 per cent more of their milk supply in their heaviest than in their lightest month.

TABLE XXVI

VARIATION IN FLOOR SPACE PER THOUSAND POUNDS OUTPUT, SQUARE FEET

Groups	No. in group	Average of group	Output
Under 6	7	4.5	521,611
6 to 10	26	7.9	309,522
10 to 13	16	11.7	119,982
13 to 18	23	15.0	171,883
18 to 22	10	20.4	127,316
22 and over	9	29.9	89,850
All creameries	91	10.8	230,011

Because of the combination of all the foregoing factors, there is a wide range in the utilization of space. Table XXVI shows that even the ordinary range is from 6 to 22 square feet per 1000 pounds of output.

Creamery sites.—Table XXVII shows the size of the building sites occupied by 80 creameries classified as to whether located in cities, villages, or the country. In cities, an ordinary city lot is most commonly used; in villages, a half-acre; and in the country, a half-acre or an acre.

TABLE XXVII

SIZE OF LOT OCCUPIED BY 80 MINNESOTA CREAMERIES

Size of lots in fractions of acres	Number of creameries occupying lots of varying sizes in			
	Cities	Villages	Country	Totals
Three	..	2	..	2
Two	1	1	..	2
Between one and two	1	5	2	8
One	3	5	6	14
Between one and one half	1	7	1	9
One half	1	11	5	17
Between one half and one quarter	4	4	..	8
One quarter	6	4	..	10
Under one quarter	6	4	..	10

Building cost per square foot of floor space.—Table XXVIII shows that interest on investment is the largest expense connected with the creamery building, constituting 50.5 per cent of the total. The various expenses were computed as follows:

Interest.—Interest was computed at the prevailing rate on similar investments in the locality. The rates used were 6 per cent for 4 creameries and 7 per cent for 84 creameries. An attempt was made to value buildings on the basis of cost of construction at the time of the survey, less depreciation to that date. It was only partly successful. The average original cost of construction of the 88 creamery buildings was $7304. If they had been constructed in 1920, they probably would have cost $12,890. The depreciation on this basis would have been

$3530, making the 1920 valuation $9360. The depreciation on the original cost basis of $7304 would have been $2008, making the 1920 valuation $5296. The actual valuation obtained was $7400, which is almost exactly half-way between the two.[16] Interest was based on this $7400 valuation.

As will appear later, this was an unsatisfactory method of computing interest charges. Interest should have been based on the average value per year throughout the life of the building, in other words, one half of the present cost of reproduction. According to the method used, brick buildings, because only one-seventh depreciated, have a much higher interest charge in proportion to their present value than the frame buildings which are three-fourths depreciated.

Taxes.—The actual taxes paid were included. Income taxes should not properly have been charged to real estate, but it was impossible to make the separation in the annual reports of the creameries, and besides very few creameries paid income taxes.

TABLE XXVIII

DIVISION OF ANNUAL EXPENSES CONNECTED WITH 88 CREAMERY BUILDINGS

Items of expense	Average expense		Per cent of total building expenses
	Per creamery	Per 1000 pounds of butter	
Taxes	$113	$0.49	11.1
Insurance	32	0.13	3.0
Interest	515	2.21	50.5
Depreciation	263	1.13	25.9
Maintenance	97	0.42	9.5
All building expense	$1020	$4.38	100.0

Insurance.—The insurance was computed by using the rate per year. Most of the creameries of the state are insured in the Mutual Creamery and Cheese Factory Fire Insurance Company of Minnesota. The schedule of rates on policies in this association is as follows:

> Sec. 3. A premium of one per cent of the amount of insurance applied for shall be paid by the applicant on class A and B risks: 65 per cent of the A rate on class C risks and 50 of A rate on class D risks. The classification is as follows:
>
> Class A, wooden buildings equipped with steel stacks.
>
> Class B, wooden buildings equipped with brick stacks.
>
> Class C, buildings of stone, brick or concrete with wooden shingle roofs, equipped with brick or concrete chimney and stacks.
>
> Class D, buildings of stone, brick or concrete walls, the roofs of which are covered with fire proof material and equipped with brick or concrete chimney and stacks.

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[16] This discrepancy may be simply because in periods of rising prices our notions of building costs are sure to lag; or it may include a considerable recognition of the obsolescence surely present.

> In the levying of an assesssment the rate on class B shall be 80 per cent of the rate on class A and the rate on class D 50 per cent of the rate on class A.

Depreciation.—Annual depreciation was computed by dividing the 1920 valuation of the building by its estimated life. The estimated life of a building was based on general estimates for the various types of construction, modified to fit the particular condition of the different buildings at the time of the visit. The estimated life of the brick buildings was most commonly 50 years; of the ordinary frame structure, from 20 to 30 years, the range being 15 to 45 years, depending largely on the care received; of concrete buildings, from 30 to 50 years; and of hollow-tile creameries, 50 years. There were a few combination brick and frame structures. The average life of these buildings was 27 years. These estimates represented the combined judgment of creamery architects, creamery operators and officers, and the man making the survey.

Maintenance.—This includes the annual cost of labor, materials, etc., for repairs and renewals, such as painting and roofing. Labor is usually a larger item than materials.

The ordinary range in annual cost per square foot of the creamery building and site combined is indicated in Table XXIX. This cost is sixteen times as much per square foot, and eighteen times as much per creamery, for the 20 highest creameries as for the 10 lowest. The extreme range per creamery is from $80 to $3240, and per square foot, from 3 to 95 cents.

TABLE XXIX

RANGE IN ANNUAL SPACE COST

Groups	No. in group	Average for group			Annual space cost per creamery		
		Building	Site	Both	Building	Site	Both
Cents square foot		Cts. sq. ft.	Cts. sq. ft.	Cts. sq. ft.	Sq. ft.	Sq. ft.	Sq. ft.
Less than 10	2	4.8	0.0	4.8	$106	$00	$106
10 to 20	12	14.6	1.0	15.6	347	24	371
20 to 30	15	23.4	1.9	25.3	605	43	647
30 to 40	13	32.8	2.2	35.0	722	45	767
40 to 50	16	43.3	1.8	45.1	1115	56	1172
50 to 60	10	51.8	4.0	55.8	1262	96	1358
Over 60	20	70.3	5.8	76.1	1820	148	1968
All	88	40.7	2.9	43.6	$1020	$72	$1092

Part of the reason for this extreme range is difference in the cost of the creamery site. Table XXX shows the variation in site cost. The extreme range for purchased sites is from less than half a cent to ten cents per square foot of floor space. In addition, thirteen of the sites were either donated or leased for a nominal consideration. On the other hand, one creamery with an output of 106,000 pounds paid $5000 for its site; and a creamery with an output of 482,000 paid $8000 for its site. Eleven sites cost $200 or over. Tables XXXI and XXXII show the relation of site cost to type of community in which located. Creameries with locations in cities usually keep site cost within reasonable bounds by building on either one or two lots.

TABLE XXX

VARIATION IN ANNUAL COST OF SITE

Groups	No. in group	Average for group	Average cost per 1000 pounds of butter
Cents per square foot		Cts. per sq. ft.	Cents
None	13	None	0.0
0 to 1	17	0.87	9.1
1 to 2	27	2.24	14.0
2 to 3	10	3.66	52.7
3 to 4	5	5.29	50.2
4 to 5	3	6.87	63.4
5 and over	7	10.96	120.1
All	82	2.88	30.9

The average annual site cost is $72 per creamery. It consists of $67 of interest plus $5 of taxes. The attempted basis of valuation was cost to purchase at land prices in 1920, but, as in the case of buildings, this was only partly accomplished. The average first cost of the sites, as given in Table XXXI, was $1193. The average valuation obtained was $1720. The interest rate applied ranges from 2 to 5 per cent, being 4 per cent in most cases. The average was 3.9 per cent. These rates represent the prevailing ratios, as nearly as can be estimated, between prevailing annual net incomes from land and valuations in 1920. The ratios between net incomes and values of farm lands in Minnesota in 1919, as derived from the 1920 census schedules by C. R. Chambers, of the United States Department of Agriculture, ranged mostly from 2 to 4. The ratios for land in cities and villages are usually around 4.

TABLE XXXI

FIRST COST OF SITE FOR MINNESOTA CREAMERIES

Location	First cost of site
Country	$227
Village (edge of)	623
Village (center of)	1447
City (edge of)	1612
City (center of)	2316
All creameries	$1193

The extreme range in annual building cost alone per square foot of floor space is from 3 to 90 cents, and the ordinary range is from 15 to 75 cents. The value of the building is of course the principal determiner of annual building costs; the other determinants are rate of depreciation and cost of maintenance. The wide range in valuations can not escape producing a wide range in annual space costs. Two buildings were valued at $500 each, one at $35,000, and one at $29,110. This range is of course due to two things, high original cost, and small amount of total depreciation because of the newness of the buildings.

TABLE XXXII

FIRST COST PER ACRE OF SITES FOR MINNESOTA CREAMERIES

Location	Average cost per acre
Country	$710
Village or city (population)	
0 to 499	2340
500 to 999	2045
1000 to 1999	5809
2000 to 2999	6885
3000 to 3999	2564 (2 only)
4000 and over	7142

Table XXXIII shows this relation in detail. The high construction cost of the brick and tile buildings and their newness gives a relatively high annual interest charge. Lower depreciation and maintenance costs offset only a little. The higher cost of construction largely offsets the longer life, so that depreciation is only 2.9 cents less per foot for brick than for frame buildings. The brick buildings in 1920 averaged only 7.1 years old, and the frame buildings 18 years old. The first effect of this is that the brick buildings were therefore built under a higher price level than the frame buildings. An attempt is made to correct for this in Table XXXIV. Figure 19 shows the changes in creamery building costs per square foot from 1897 to 1920. The figures are estimates based partly on actual creamery costs and partly on prices of building material and labor as published by the United States Bureau of Labor.[17] All were reduced to a 1914 price level basis, this being a better base year for such a comparison than 1920. The brick buildings, if all were built in 1914, would have cost $913 less, or 33 cents (11 per cent) less per square foot; and the frame buildings $582 more, or 29 cents (21 per cent) more per square foot. Making allowance for this, the interest and depreciation charges on brick buildings would be 31.4 cents per square foot instead of 35.3. And the interest charge and depreciation charge on frame buildings would be 19.3 cents per square foot instead of 16.4. The maintenance charge would be similarly affected, because it is largely proportional to first cost. Thus, annual space costs on brick buildings would be reduced probably to 43 cents; and on frame buildings, raised to about 32 cents.

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[17] One of the principal difficulties connected with these data is the apparent improvement in the quality of the construction, especially of brick buildings, in recent years. This was corrected for, but inadequately.

TABLE XXXIII

Relation of Depreciation, Interest, and Maintenance Costs by Type of Construction

Type of construction	No. of creameries	Construction cost per square foot	Annual building cost per square foot	Percentage of annual building cost due to			Annual cost, per square foot		
				Depreciation	Interest	Maintenance	Depreciation	Interest	Maintenance
			Cents				Cents	Cents	Cents
Brick	50	$3.50	47.7	18.4	55.6	11.3	8.8	26.5	5.4
Frame	25	1.40	28.4	41.2	20.0	25.3	11.7	5.7	7.2
Brick and frame....	5	2.47	34.8	31.3	37.4	19.5	10.9	13.0	6.8
Concrete	4	2.04	30.9	20.4	50.5	14.6	6.3	15.6	4.5
Tile	4	3.36	47.3	16.9	59.2	10.8	8.0	28.0	5.1
All creameries*..	88	$2.84	40.7	23.6	47.7	14.5	9.6	19.4	5.9

* Averages weighted by size of buildings.

TABLE XXXIV

AGE, COST, AND TYPE OF CONSTRUCTION OF 88 CREAMERIES

Type of construction	No. of creameries	Average age of buildings	Average cost			
			Per creamery		Per square foot*	
			When built	If built in 1914	When built	If built in 1914†
Brick	50	7.1	$9825	$8908	$3.50	$3.17
Frame	25	18.0	2810	3392	1.40	1.69
Brick and frame	5	12.4	5650	4058	2.47	2.68
Concrete	4	12.3	4573	6142	2.04	1.81
Tile	4	6.0	8625	7735	3.36	3.01
All	88	10.7	$7304	$7207	$2.88	$2.56

* Averages weighted by size of buildings.

† Adjustments made on basis of Figure 20.

The second effect is that according to the system of valuation used the interest charge on brick buildings is based on a value depreciated by only 7.1 years, or 14.2 per cent, whereas frame buildings are based on a value depreciated 18 years, or 72 per cent. If interest charges for brick buildings had been based on an average of 50 per cent depreciation from the values obtained in the survey, the average would have been $420 per creamery, or 15.0 cents per square foot. For frame buildings, the comparable figures would have been $243 per creamery, or 12.1 cents per square foot.

If these two effects are eliminated, the comparable figures for building costs would be as follows: brick, 31.5 cents per square foot; frame, 38.4 cents per square foot.

The maintenance costs given in Table XXXIII must not be accepted as at all accurate. There is reason for believing that they are all too high. It was difficult to secure good estimates as to most of the items of cost included.

It is probably true that brick buildings provide cheaper space than frame buildings, provided the brick creamery buildings do not become obsolescent long before they are worn out. As already pointed out, rapid changes are taking place in the whole organization of the creamery business, and no doubt many brick creamery buildings will go out of use long before the 50 years of estimated life is past.

Providing cheap space, however, is by no means the sole objective in planning a creamery—a fraction of a cent more due to the quality of the cream received or butter made would easily pay the additional cost.

TABLE XXXV

COST OF CONSTRUCTION BY TYPE OF BUILDING AND SIZE

Floor-space	No. of creameries	Cost of construction per square foot				
		Brick (50)*	Frame (25)	Concrete (4)	Tile (4)	Brick and frame (5)
Sq. ft.						
Less than 1500	6	....	$1.68	....	....	....
1500 to 2000	17	$2.89	1.41	$2.10	$2.87	$2.91
2000 to 2500	22	2.32	1.77	1.88	5.81	3.44
2500 to 3000	25	3.15	1.35	2.12	....	1.38
3000 to 3500	12	3.91	....	....	2.72	....
3500 to 4000	3	4.94	0.99	....	....	....
4000 to 4500	2	5.88	....	....	....	....
4500 and over	1	5.64	....	....	....	....
All creameries†	88	$3.50	$1.40	$2.04	$3.36	$2.47

* Number of buildings.

† Average weighted by size of buildings.

Table XXXV shows the interesting fact that apparently construction cost per square foot of brick buildings increases with the size of the building. Most of this is due to the fact that the larger buildings were erected more recently and are also of better construction. With frame buildings, the opposite tendency prevails.

Space costs (building and site), when reduced to an annual cost per square foot basis, show no correlation whatever with output, that is, they are the same for creameries with large output as for creameries with small output.

The ordinary range in construction costs per square foot of brick creameries, as given in Table XXXV, except for six expensive creameries recently built, is from $1.50 to $4 when the costs are all reduced to the 1914 price level; and the ordinary range in annual space cost from 25 to 51 cents per square foot.

TABLE XXXVI

VARIATIONS IN CONSTRUCTION COSTS OF BRICK CREAMERIES

Groups (construction cost when built)	No. in group	Average cost per square foot of construction		Annual space cost per square foot	
		When built	If built in 1914	When built	If built in 1914
				Cents	Cents
Less than $2	10	$1.42	$1.52	22	24
$2 to $3	9	2.56	2.73	44	45
3 to 4	14	3.57	3.34	46	43
4 to 5	11	4.41	3.70	63	51
5 to 6	..	....	....	..	..
6 to 7	3	6.48	4.18	78	49
Over 7	3	7.31	7.45	85	87
All creameries	50	$3.50	$3.17	48	43

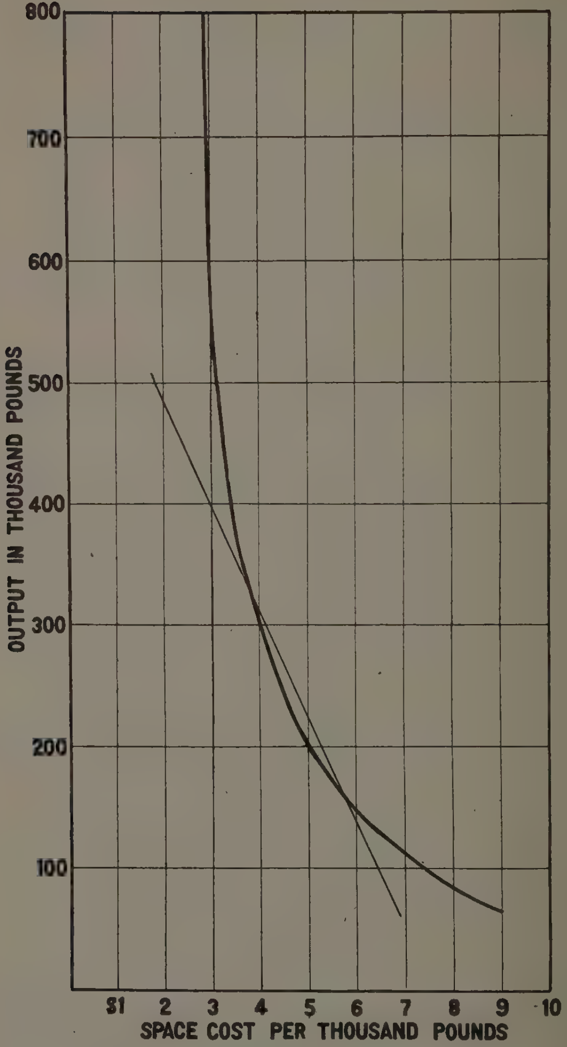

Fig. 20. Relation of Space Cost to Output

Most of the saving in space cost with larger output comes under 300,000 pounds.

TABLE XXXVII

VARIATIONS IN ANNUAL COST OF BUILDING SPACE PER 1000 POUNDS OF BUTTER

Group	No. in group	Average of group	Average per creamery
$1 to $2	14	$1.48	$503
2 to 3	17	2.75	462
3 to 4	14	3.50	908
4 to 5	9	4.63	1186
5 to 6	9	5.40	1437
6 to 7	5	6.68	1260
7 to 8	6	7.66	1795
8 to 9	4	8.49	1148
9 to 10	6	9.53	1491
10 and over	4	13.85	1878
All creameries	88	$4.38	$1020

Space cost per 1000 pounds butter.—While 15 creameries have building costs of less than $2 per 1000 pounds of butter, according to Table XXXVII, 4 have building costs over $10 per 1000 pounds of butter. The highest cost, $15.35 per 1000, is for a creamery with 3136 square feet of floor-space costing $18,000 to build, making only 131,000 pounds of butter in 1919. The lowest cost, $1.16 per 1000, is for a creamery with 2530 square feet of floor-space costing $8000, making 544,000 pounds of butter in 1919. The average for 88 creameries is $4.38 per 1000 pounds of butter.

TABLE XXXVIII

VARIATION IN ANNUAL SITE COST PER 1000 POUNDS OF BUTTER

Groups	No. in group	Average for group	Average output
Cents		Cents	Lbs.
None	13	None	243,000
0 to 10	13	6.1	291,000
10 to 20	17	12.5	273,000
20 to 30	16	24.6	196,000
30 to 50	14	40.2	211,000
50 to 60	5	67.0	191,000
60 and over	10	111.5	185,000
All	88	30.9	233,300

Site cost per 1000 pounds of output has an ordinary range, according to Table XXXVIII, between 10 and 15 cents per 1000. The highest site cost, $2.85 per 1000, is for a creamery making only 106,000 pounds of butter in 1919 which paid $5000 for its site. The next highest, $1.11 per 1000, is for a creamery making 110,000 pounds in 1919 which paid $2000 for its site. The next highest, 92 cents per 1000, is for a creamery making 482,000 pounds in 1919 which paid $8000 for its site. The average is 30.9 cents per 1000. This combined with $4.38 gives a total space cost of $4.68 per 1000.

The cost of "extra space" in creameries, according to Table XXV (see p. 17) is 52 cents per 1000 pounds. Thus it is a more important element of cost than site.

TABLE XXXIX

FIRST COST OF SITE PER 1000 POUNDS OF BUTTER

Groups	Number of creameries			
	City	Village	Country	All
Donated	..	2	4	6
Lease	2	2	2	6
Less than $2	2	11	4	17
$2 to $4	5	11	1	17
4 to 6	7	8	..	15
6 to 8	2	5	..	7
8 to 10	2	1	..	3
10 to 12	1	2	..	3
12 to 14	..	1	..	1
14 to 16	3	1	..	4
$16 and over	3	1	..	4
All creameries	27	45	11	83

Table XXXIX expresses first cost of site as a ratio to output in 1919. Four creameries paid for their site $16 or over for each 1000 pounds of output from their plant. The average is $5.05 for all creameries, $7.65 for creameries located in cities, $4.65 for creameries located in villages, and 80 cents for creameries located in the country. These figures may indicate when the purchase price of a site is out of proportion to the volume of business.

Space cost per 1000 pounds of butter varies principally with output and with its two components, namely, square feet per thousand, and annual cost per square foot, both of which have been analyzed above. Figure 20 shows how space cost per 1000 pounds of butter varies with output. On the average, each additional 100,000 pounds of output, taking the creameries as they are, that is, other things not being equal, means $1.14 less annual space cost (25.5 per cent) per 1000 pounds of output, as indicated by the straight line. From 100,000 to 300,000 pounds, however, the decrease is at the rate of $1.68 per 1000 for each 100,000 pounds, as indicated by the curved line. This curve for output and space cost represents a combination of the significant curve for utilization and output (Fig. 17), and the lack of correlation between cost per square foot and output mentioned on page 55.

Figure 21 shows how space cost per 1000 pounds of butter varies with annual cost per square foot and with square feet per 1000 pounds output, with building values and interest based as in this analysis. If space cost per 1000 pounds were exactly proportional to cost per square foot, 10 cents additional cost per square foot would mean $1.08 additional space cost per 1000 pounds of output ($\$0.10 \times 10.84 = \$1.084$).

Figure 21 shows, that the actual average increase is $1.30. For creameries with space costs over 50 per cent above the average, however, the space cost per pound of butter increases much more slowly (see accompanying curved line). If space cost per 1000 pounds were proportional to the number of square feet per 1000 pounds, then one additional square foot per 1000 pounds would mean an increase in cost of 4.36 cents per 1000 pounds of butter (4.36×1=4.36). Figure 21 shows that the actual increase is only 2.83 cents. The reason for this is that the poorest utilization of space (most square feet per 1000 pounds) usually occurs in creameries where cost per square foot is lowest.[18] The accompanying curved line shows that the increase in space cost with square feet per 1000 was at first more rapid than the average and then less rapid. Taking creameries as they are, cost per square foot is obviously having more effect than utilization of space on the unit space costs of a creamery.

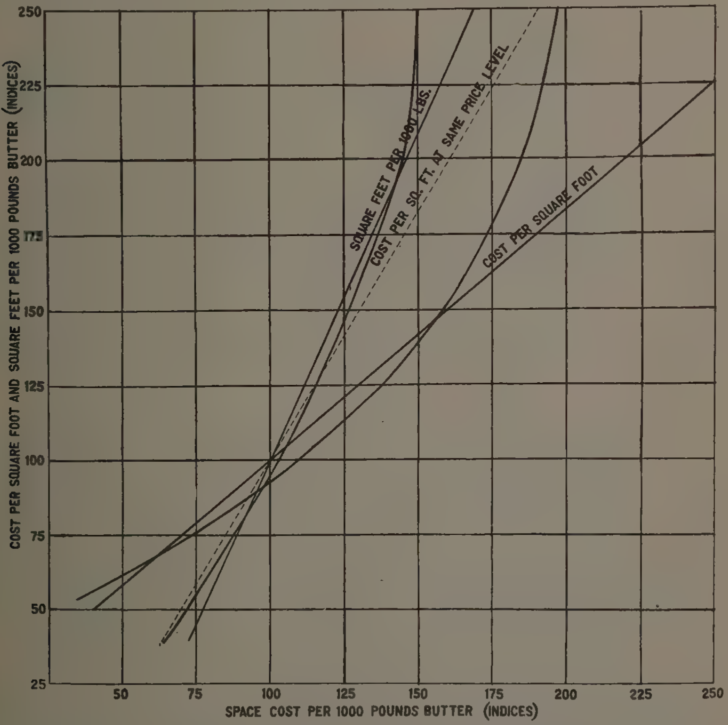

Fig. 21. Relation of Space Cost to Output

Annual cost per square foot affects space cost more than the utilization of space; but this would be much less true if all valuations and interest charges were on the same basis. The curved lines express the relationships in more detail than the straight or average lines.

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[18] Inverse correlation.

When this analysis is made for brick and frame creameries separately, it appears that cost per square foot affects space cost 35 per cent more for frame creameries than for brick creameries. This is because there is a wider range in value of frame buildings. On the other hand, utilization of space affects space costs 140 per cent more for brick buildings than for frame buildings. This is because the frame buildings are old and are likely to be used to capacity, whereas many of the new brick buildings were built much larger than present receipts warrant.

As above explained, the method used of valuing buildings and charging interest is subject to serious criticism for the purposes in question. Those in charge of creamery organizations are interested in what space costs will be and how they will be affected by building costs at the prevailing price level, not at the price level which happened to prevail when the building was constructed. They are interested in the interest cost over the whole period of use of the building, and not in the interest on only that portion of the building which is not yet worn out. Handling valuations and interest in this way also destroys a large part of the correlation that should exist between output, cost, and the other factors. Were this study to be repeated, therefore, all values would be reduced to a common basis and interest would be based on a 50 per cent depreciation. The attempt to do this subsequently as part of the analysis has been only partly successful. The dotted straight line in Figure 21 shows costs per square foot on this basis increasing space costs per thousand at the rate of 65 cents for each 10 cents additional cost per square foot, in place of $1.30 on the first-cost basis. Most of the pronounced effect of cost per square foot is therefore due to the method of handling valuations and interest.

EQUIPMENT COST

Under equipment was included the boiler and engine, churns, vats, starter cans, Babcock testers, office desks, typewriters, and all major articles. Such items as thermometers, brushes, and pails were charged as materials under supplies and miscellaneous. Table XL shows that the total annual cost of equipment of 88 creameries in 1919 averaged $929, or leaving out sidelines and hauling, $886. Only 6 do hauling, and only 15 have important sideline equipment. The equipment for reparation for churning and that for churning have the highest annual cost. Equipment costs will be analyzed in more detail under process costs.

Table XLI shows that depreciation, maintenance, and interest costs re about equal and make up 92.6 per cent of the total.

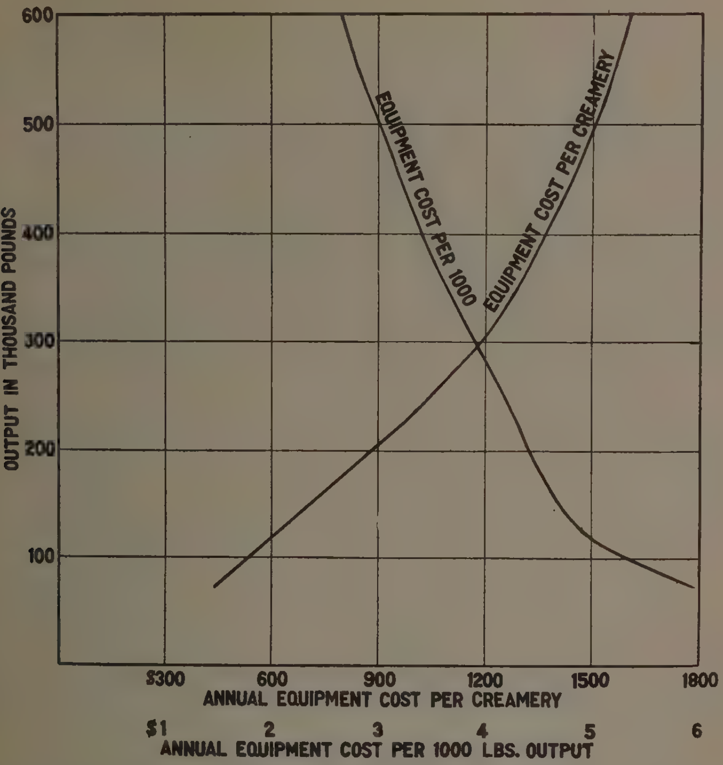

Fig. 22. Relation of Equipment Cost to Output

Equipment costs per thousand decrease rapidly up to the point of full utilization of minimum-sized equipment, and less rapidly from then on.

Interest and depreciation were determined on the same basis as for buildings. The valuations, as near as can be determined, average about half way between cost when purchased and cost in 1920 less depreciation to date. The equipment averaged 30 per cent worn out at the time of the survey. The average value for equipment per creamery was $4050. The cost of equipment new in 1920 was estimated at $5800. This depreciated 30 per cent would make a total depreciation of $1750, or $407 per year. The actual cost of the equipment new in 1920 would probably have been between $6000 and $7000. The interest rate was practically the same as for buildings, 7 per cent in most cases. The estimates of life of equipment were made by the creamery operator, in the first instance, but were verified when possible from other sources, such as creamery supply houses. The average for all equipment combined was 14.4 years. All important renewals were analyzed separately from general depreciation wherever possible. Labor and materials are the principal items in maintenance cost.

Taxes and insurance were handled as for buildings.

Table XL shows the equipment costs directly charged to the different processes. Power, water, and cold storage are of course later redistributed to the remaining processes. Preparation for churning and churning are the two largest items in equipment cost.

TABLE XL

Distribution of Equipment Costs by Processes

Process	Average equipment cost per creamery	Per cent of total equipment cost
Receiving	$54	5.7
Babcock testing	15	1.6
Preparation for churning	271	29.2
Churning	167	18.0
Record keeping and correspondence	49	5.2
Preparation for marketing	39	4.2
Cold storage	114	12.3
Power	135	14.5
Water	20	2.2
General maintenance	9	1.0
Skimmilk and buttermilk disposal	13	1.4
Hauling	25	2.7
Sidelines	18	2.0
All processes	929	100.0

TABLE XLI

Elements of Equipment Cost (Excluding Sidelines and Hauling)

Items of expense	Average expense		Per cent of total equipment expense
	For creamery	Per 1000 pounds of butter	
Interest	$267	$1.15	30.1
Taxes	49	0.21	5.5
Insurance	17	0.07	2.0
Depreciation	407	1.75	45.9
Maintenance	146	0.63	16.5
All equipment expense	$886	$3.81	100.0

Range in equipment costs.—The range in annual equipment costs is from $300 to $2100. Eight creameries have equipment costs over $1500, twenty-six over $1000, and fifteen under $500. The range per 1000 pounds of butter was from $1.38 to $9.63, ten having costs under $3 per 1000, and eight over $6 per 1000. The average annual cost of equipment per 1000 pounds of output was $3.98; or, excluding hauling and sidelines, $3.81.

The analysis of reasons for variations in equipment cost should follow the same lines as that for building cost. The variations can be said to be due to variations in the annual cost of the equipment and in the utilization of the equipment. Reduced to more definite terms, the annual cost, let us say, of churning equipment is equal to the product of annual cost per 100 pounds of churn capacity times the output of the creamery for each 100 pounds of churn capacity. The following analysis of churn equipment is introduced merely as an example of the form of analysis. If equipment costs are to be analyzed thoroly, a study must be made for each item of equipment separately, as the various items of equipment have no common unit of size. Just as labor has been measured in hours and space in square feet, so churns must be measured in one way, Babcock testers in another, and ripeners in another. The only possible common unit of measurement is value or cost; and using this unit covers up exactly what one wishes to show.

TABLE XLII

VARIATIONS IN CHURN CAPACITY

Capacities	No. of creameries	Butter output, in 1000's	
		Average	Range
Lbs.		Lbs.	Lbs.
One churn			
500	1	69	69
600	2	95	95
700	3	71	41 to 96
800	8	145	44 to 256
900	8	113	75 to 134
1000	28	171	59 to 245
1200	1	554	554
Two churns			
1400	3	144	140 to 148
1500	5	199	190 to 215
1600	2	325	207 to 433
1700	9	217	135 to 293
1900	2	338	307 to 361
2000	12	453	347 to 886

Table XLII shows that churn capacity and output are very poorly matched in the various creameries. For example, one creamery with an output of 59,000 is using a 1000-pound churn; and another with an output of 256,000 is using only an 800-pound churn. A 1200-pound churn is turning out 554,000 pounds, and a 1700-pound churn capacity, only 135,000 pounds. These misfits are due to various causes, chief of which are the following: extra capacity provided for expansion which has not yet come; extra heavy peak-load requirements in May and June, with low receipts in the fall and winter. Or sometimes where two churns are used one is old and used only at peak-load periods. The creameries with relatively small churn capacity get along by churning every day and sometimes two or even three times a day during flush periods. Those at the other extreme churn every other day in the winter, or even less often, and must run their churns under capacity much of the time. Table XLIII shows that the outputs of the 91 creameries represent an average of only 167 full churn loadings. The extreme range is from 55 to 453, and 4 have an average of only 70 full churn loads.

TABLE XLIII

Variations in Number of Full Churn Loadings with Output*

Groups (output)	Number in group	Average for group
Lbs.		Lbs.
Under 100	11	69
100 to 150	20	128
150 to 200	18	170
200 to 300	25	238
Over 300	17	385
All	91	167

* Assuming that cream could be held until the churn could be filled each time.

Table XLIV shows how churn capacity increases with output in the 91 creameries used in this particular analysis. The average churn capacity of the 91 creameries is 1240 pounds, or 5.3 pounds for each 1000 pounds of annual output. The extreme range is from 2.0 pounds per 1000 for a creamery with 491,000 pounds of output with a 1000-pound churn, to 18.2 pounds for a creamery with 44,000 pounds of output and an 800-pound churn. Fifteen of the 91 have less than 5 pounds, and 8 have more than 10 pounds, per 1000 pounds of output. Under 200,000 pounds of output, the decrease in churn capacity per 1000 pounds of output is rapid, but above this point it is much slower. This is because a 1000-pound churn can handle 200,000 pounds of output in most cases, but it can not conveniently handle much more. Only 7 creameries under 200,000 pounds have more than 1000 pounds capacity, and only 10 over 200,000 pounds are getting along with 1000 pounds capacity.

TABLE XLIV

Variations with Output in Churn Capacity per 1000 Pounds Output

Groups (output)	No. in group	Average output	Average capacity	Capacity per 1000 pounds output
Lbs.		Lbs.	Lbs.	Lbs.
Under 100	11	72,800	780	10.7
100 to 150	20	128,900	1060	8.2
150 to 200	18	184,500	1090	5.9
200 to 300	25	240,000	1230	5.1
300 and over	17	480,000	1800	3.7
All	91	233,000	1240	5.3

The other factor in churn equipment cost is the annual cost per unit of churn capacity. The principal factor in this is the first cost of the churn. The oldest churn in use at the time of the survey was bought in 1910, and 8 were installed in 1912. Between 1912 and 1920, the price of churns doubled. The valuation given at the time of the survey was based partly on these varying prices depreciated to date. Interest and depreciation changes are based on these valuations. This results in a wide range in annual costs per unit of capacity.

The rate of depreciation is also a factor in the cost. The average time since the purchase of all the churns was 4.4 years. The average estimated life was 8.6 years. These estimates check closely, for over a period of time and in an industry which is in a stable condition, the estimated life should be twice the average age of the churns now in use. The range in estimated life was from 5 to 12 years, 7, 8, and 10 years being named most frequently. No correlation was discovered between estimated life and output per churn capacity. The variations seem to be due mostly to differences in upkeep and in the judgment of the operators as to the probable life of the churn. The extreme range in churn cost was from $9 per 100 pounds churn capacity for a 1000-pound churn bought in 1913, with an estimated life of twelve years, to $34 per 100 pounds capacity for an 800-pound churn bought in 1919, with an estimated life of five years. The average was $21 per 100 pounds capacity.

Reduced to the basis of annual cost, the ordinary range is from 60 cents to $2 per 1000 pounds of output. The highest cost, $3.10, is for a creamery making 75,000 pounds of butter in 1919 which bought a 900-pound churn that year. The average was $1.08 per 1000.

A change from 5.3 pounds of churn capacity per 1000 pounds of output, the average, either upward or downward one pound would, taking other circumstances as they are, have increased or decreased churn equipment costs by 25 cents per 1000. A change in cost per 100 pounds of churn capacity from $21, the average, either upward or downward by $1, would, other things being as they are, have increased or decreased churn equipment costs 20 cents per 1000. This means that variations in cost of the churn were three times as responsible for the differences in churn equipment costs as the differences in utilization of the churn. This is because of the wide range in valuations due to the wide variations in price paid for churns from 1912 to 1920. In normal times, the various makes of churns sell at about the same price; hence any differences would be due to differences in rate of depreciation and upkeep, or in cost per unit of capacity with different sized churns. Utilization would therefore be relatively much more significant in normal times, or if the churns had been valued on a common basis.

On an output basis, the range in churn cost is from $1.75 per 1000 for the smallest 10 creameries to 75 cents for the largest 10 creameries.

The decrease in cost is at a rate increasing somewhat rapidly below 250,000 pounds of output.

If a similar analysis were made for each item of equipment, similar results would be obtained. In each case, it would be discovered that utilization varied, and in consequence, the resulting equipment cost; and likewise the annual cost per unit of capacity would vary, depending, however, owing to the method of valuation used, largely upon prices paid at different price levels, and also upon rate of depreciation, upkeep cost, etc. The range in utilization varies, of course, with different items of equipment. In general the smaller the unit and the sooner it wears out, the better the utilization, as this makes it possible to fit sizes better to volume of business.

Figure 22 shows variations with output of annual equipment cost per creamery and per 1000 pounds of butter. At 500,000 pounds output, the equipment cost is $3 per thousand, or $1500 per creamery; at 200,000 pounds output, it is $4.40 per thousand, or $880 per creamery. The savings in equipment cost with output are considerable, but not so much as for labor and management or for buildings and space. This is because much of the equipment is in small units, making possible a better adjustment of capacities.

According to the valuations obtained in the survey, the value of equipment in 1920 was $4050 per creamery, as compared with $7400 for buildings. This equipment represented 35.4 per cent of the value of plant and equipment. If each had been depreciated to the same extent, however, say 30 per cent, the figure would have been 36.1 instead of 35.4. It is 4 per cent higher for brick buildings than for frame buildings. These figures are merely averages, of course, and do not fit any particular plant at any time. The figure 36.1 per cent given above ought not to be very far from the average ratio between investment in buildings and equipment at any equal stage in depreciation. In a new creamery, however, the equipment will depreciate more rapidly than the plant (3.5 times as fast as for brick buildings) so that the ratio of value of equipment to value of buildings will constantly decline till the equipment begins to be replaced.

SUPPLIES AND MISCELLANEOUS CASH EXPENSES

As already explained, this is the largest classification of expense items in 1919, constituting 45 per cent of the total expenses of a creamery. Table XLV lists the most important items in their relative importance. The relative importance of these items will of course change as prices change.

TABLE XLV

ITEMS INCLUDED UNDER SUPPLIES AND MISCELLANEOUS CASH OUTLAYS

Items	Average cost per creamery 1919	Per cent of total cost
Tubs and boxes	$1875	43.9
Fuel and electric power	755	17.7
Drayage	190	4.5
Liners and circles	180	4.2
Salt	135	3.2
Stationery	80	1.9
Color	60	1.4
Paraffin	50	1.2
Washing powder	40	0.9
Acid	35	0.8
Oil	35	0.8
Tub tins	25	0.6
Light	20	0.5
Miscellaneous	787	18.4
Total	$4267	100.0

Included in miscellaneous are such items as the following: ice, water, ammonia, starter culture, wrappers, repairs, glassware, brushes, thermometers, cotton waste, boiler compound, telephone, printing, advertising, and membership fees in creamery organizations. Ice is the largest expense in this miscellaneous group, and was not listed separately because many of the creameries have ice machines. Similarly, many of the creameries supply their own water. Starter culture averaged $20 for those creameries using it. Wrappers are used in greatly varying proportions by different creameries. The average was $60 for those using an appreciable quantity of them.

The range in costs for this group of expenses is from $12 to $34 per 1000; but all except a few of the costs come between $14 and $26 per 1000 pounds. The average is $18. It will be realized that this figure is somewhat higher than now prevails because the costs of most supplies have fallen considerably. There is also a considerable margin of error in these figures due to the difficulty of getting accurate estimates of opening and closing inventories for the various supply accounts.

The principal reason for the variations in supplies and miscellaneous is in the fuel and electric power cost, which shows a considerable range between creameries according to output and as to whether steam or electric power is used; also according to the type of fuel used. The expense for tubs, boxes, wrappers, etc., also varies somewhat according to the method of packing the butter. The drayage cost varies according to the distance from the shipping point. The prices at which supplies were purchased varied somewhat also. On the whole, the large creameries seem to have bought most cheaply.

Figure 23 shows the variation in cost of supplies and miscellaneous with output. Above 150,000 pounds of output, the increase is noticeably less rapid. Economies in the use of fuel and buying of supplies probably account for this. Such expenses as tubs, wrappers, salt, color, and the like, making up 57.2 per cent of the total, except for economies in buying, must increase in proportion to output. The curve in Figure 23 therefore represents a combination of expenses both proportional and less than proportional to output.

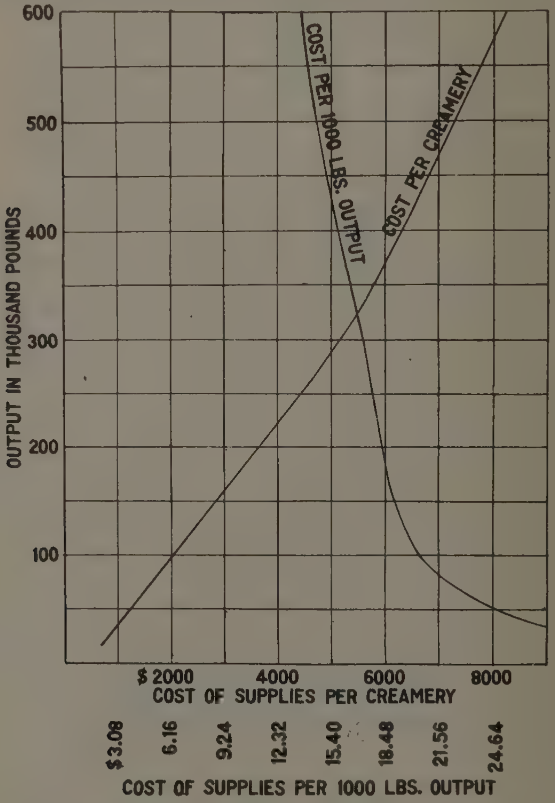

Fig. 23. Relation of Cost of Supplies to Output

Most of the decrease in cost of supplies with output is to be attributed to fuel and ice. Apparently creameries under 100,000 are wasteful of both. All of the rest of supplies are nearly proportional to output.

The direct distribution of supplies and miscellaneous cost is indicated in Table XLVI. The charge to power account was of course later redistributed to testing and other final processes; and the same for water, general maintenance, cleaning, and miscellaneous.

Following is a list of the supplies and miscellaneous items and the accounts to which they are charged:

Testing	Acid, glassware
Preparation for churn	Starter culture, milk powder
Churning	Color, salt, about one third of charge to hauling supplies
Power	Fuel, electric power, hauling fuel, oil, cotton waste, boiler compound
Cold storage	Ice, ammonia, calcium chloride
Preparation for market	Tubs and packages, liners and circles, wrappers, tub tins, paraffin, freight and drayage, about two thirds of hauling supplies.
General maintenance	Labor on repairs, thermometers, etc.
Cleaning	Washing powder, brushes
Water	Water
Heat and light	Heat and light
Miscellaneous	Sidelines; special repairs charged directly to space or equipment, etc.

TABLE XLVI

Distribution of Supplies and Miscellaneous Cost

	Average per creamery	Per cent of total
Testing	$46	1.1
Preparation for churn	20	0.5
Churning	202	4.7
Power	700	16.4
Cold storage	151	3.5
Preparation for market	2410	56.4
General maintenance	200	4.7
Cleaning	42	1.0
Water	47	1.1
Record keeping, correspondence	122	2.9
Sidelines	26	0.6
Miscellaneous	301	7.1
Total	$4267	100.0

INTERMEDIATE COSTS

Some of the basic costs of making butter and preparing it for market pass directly into the product; others pass through an intermediate stage—thus some of the supplies and labor are first converted into power and thence to the final processes. Cold storage and water represent similar intermediate stages. Cleaning, altho somewhat different, has been put in the same general class.

POWER

Table XLVII shows that supplies represent more than half the cost of power, and that space is the next most important item. In supplies are included fuel, electric power, oil, cotton waste, boiler compound, and a certain part of the freight and drayage cost.

TABLE XLVII

ELEMENTS OF POWER COST

Elements of cost	Cost per creamery			
	Amount		Per cent of total	
Equipment	$135		11.5	
Taxes		$7		0.6
Insurance		3		0.3
Interest		46		3.9
Depreciation		40		3.4
Maintenance		39		3.3
Supplies	700		9.4	
Labor	176		64.9	
Total without space	$1011		85.8	
Space	168		14.2	
Total with space	$1179		100.0	

Power cost varies because different creameries use it for different purposes. Bulletin 747 of the United States Department of Agriculture gives the distribution of heat energy in an ordinary all-steam plant making 500,000 pounds of butter and using only natural ice for refrigeration.[19] According to this bulletin, 85.3 per cent of the total heat units in the fuel are lost in the boiler room in raising steam, in the chimney to maintain draft, through the grates, etc. Thus only 14.7 per cent are delivered to the engine room.[20] Of this 14.7 per cent delivered to the engine room, the engine, as indicated in Table XLVIII, in creameries pasteurizing the cream, uses 68.6 per cent; and 31.4 per cent is used as live steam for pasteurizing, heating wash water, etc. Of the 68.6 per cent used by the engine, only 6.8 per cent is converted into useful belt work, all the rest being lost in exhaust steam, engine friction, and transmission. In creameries not pasteurizing, only 13.3 per cent of the heat units reach the engine room, and 77.0 per cent of these 13.3 per cent are used by the engine, and 23.0 per cent as live steam.

In Table XLIX, an attempt has been made to apply these data to the 88 creameries covered in the survey; and also to distribute the power cost to the different processes using power. In the first place, 48 of the 88 creameries use electric power in place of engine power, and in the second place, 15 of the partly electric plants and 4 of the all-steam plants have ice machines. They vary also in their practices as to pasteurizing, separating, pumping water, etc. On the basis of the data in Table XLVIII, and other data obtained from manufacturers as to power requirements of ice machines, a power distribution was worked out for each plant separately, according to whether or not it used electricity for power purposes, whether or not it pasteurized, etc. In Table XLIX these individual distributions are combined into two groups on the basis of cost. In the 48 creameries using electric power, the belt power, all furnished by electric motors, represents an average of 72.5 per cent of the total power cost. In the all-steam plants, the belt-power used represents 70.5 per cent of the total power cost. More of the partly electric plants have ice machines. For the 15 partly electric creameries having ice machines, the belt power represents 78 per cent of the total power cost. For the 4 all-steam plants having ice machines, the belt power represents 76 per cent of the total power cost. These 19 creameries all pasteurize their cream.

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[19] "The Economical Use of Fuel in Milk Plants and Creameries." John T. Bowen, Technologist, Dairy Division, pp. 42-44, Table 7. 1919.

[20] In the creamery studied by Bowen, the figure was 15.4 per cent; but this included a considerable amount of separating and heating separator milk.

TABLE XLVIII

UTILIZATION OF HEAT ENERGY IN AN ORDINARY CREAMERY OF 500,000 POUNDS OUTPUT*

	Per cent distribution to different uses for creameries			
	Pasteurizing		Not pasteurizing	
Belt-power use	68.6		77.0	
Consumed in engine as useful work		6.8		7.6
Lost in exhaust steam		61.3		68.9
Lost in engine friction, radiation and transmission from engine to machinery		0.5		0.5
Live-steam use	31.4		23.0	
Heating wash water		12.3		13.8
Heating starter milk		1.4		1.5
Steaming and drying cans		6.8		7.7
Pasteurizing cream		10.9		0.0
Total	100.0		100.0	

*No ice machines included.

One chance for error in this distribution is that the data by Bowen may not fit the 88 creameries, either because they are smaller or because the operators of these 88 creameries did not exercise the same relative degree of care in the utilization of power and of live steam in the engine room, as did the operators in the plant studied. Variations in losses in the boiler room obviously do not affect the percentage distribution of what is delivered to the engine room. The total cost figures, as will be seen from Table XLVII, likewise are not affected by this possible error. The only questions are whether the smaller creameries use a larger proportion as belt power or as live steam of the power delivered to the engine room than did the 500,000-pound creamery studied by Bowen, and whether they waste a larger proportion of power in their engine or their live-steam uses. The chances are that the variations among creameries in both these particulars will largely cancel each other, and that the average distribution will not be greatly biased in either direction from the distribution in Table L.

The distribution of belt power to the different processes was made on the basis of the rated horsepower requirements of the machines, running at normal input. There are two errors involved in this, one that the power requirements of machines are frequently inaccurately stated by manufacturers, and the other that the machines frequently ran under normal input. If, however, there were the same degree of error in both these respects for the different machines, the accuracy of the distribution would not be affected. It is probable that the distribution for individual creameries is considerably in error, and that these errors only partly cancel out in the group averages.

The distribution to the different live-steam uses is based on the percentages in Bowen's tables, as given in Table XLVIII. Here again it is probable that only part of the error cancels out.

If a careful study of distribution of power costs were being made, actual tests would be made of the power required to drive the different machines at prevailing loads; and live-steam utilization would be similarly measured. The following analysis, however, does not purport to furnish accurate data. It is included, not to furnish facts as to power distribution and power cost, but to show the method which should be followed in such analysis. Table XLIX must be so interpreted. The analysis has been made as accurate as possible, however, the better to show the type of results to expect from a detailed study of accurate original data. A few important conclusions can be drawn from the data in their present more or less hypothetical form, especially after certain errors have been partly corrected by statistical methods.

Utilization.—Power cost per pound of butter is the product of horsepower-hours per pound of butter multiplied by cost per horsepower-hour. The first of these is the measure of utilization. The horsepower-hours for belt power were obtained by multiplying the horsepower required to operate each machine when running at normal input by its number of operating hours per year. This undoubtedly gives a figure which is too high.[21] Live-steam use was converted to a horsepower basis by treating it as a percentage of belt-power use.

The ordinary range in horsepower-hours, calculated in this rough way, was from 2500 to 8000, only two using less than this, and only 14 more. Nearly half of them used between 4000 and 6000 horsepower-hours. Three of the largest creameries used over 15,000 horsepower-hours. The average for the all-steam creameries was 5042, and for the partly electric, 7100. The average output of the 19 creameries having ice machines was 317,000 pounds as compared with 217,000 for the others. The average size of the 23 creameries not pasteurizing was 202,000 as compared with 244,000 for those pasteurizing.

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[21] The error involved in this, as explained above, is that different creameries did not run their equipment equally near to capacity; and power ratings of machines are inaccurate. These errors could not be avoided within the limits of the present study. Note, however, that the error is partly eliminated in one part of the analysis at the end of this section.

TABLE XLIX

Distribution of Power Cost to Different Processes in All-Steam and Partly Electric Plants*

	All-steam		Partly electric	
	Cost	Per cent of total	Cost	Per cent of total
Belt power	$725	70.4	$932	72.1
Babcock testing	$3	0.3	$5	0.4
Perparation for churn	218	21.1	229	17.7
Churning	442	43.0	523	40.4
Cold storage	62†	6.0	175‡	13.6
Live steam	304	29.6	361	27.9
Water	66	6.5	87	6.7
Preparation for churn	69	6.7	97	7.5
Receiving	60	5.8	62	4.8
Cleaning	109	10.6	113	8.7
Sidelines	...	...	2	0.2
Total	$1029	100.0	$1293	100.0

* All-steam plants averaging 196,000 pounds output. Partly electric plants averaging 263,000 pounds output.

† Average for 4 which have ice machines is $635.

‡ Average for 15 which have ice machines is $588.

Table L shows how, following the above method of calculating, output affects power requirements. The average creamery in the survey making 233,000 pounds of butter used 6160 horsepower-hours, and each 100,000 above this adds 1400 horsepower-hours to the requirements; and each 100,000 under the average subtracts 2000 horsepower-hours. A principal element in this, however, is the fact that the larger creameries nearly always pasteurize and nearly always have ice machines.

TABLE L

Relation of Output to Power Utilization, Average for All Combinations

Output	Horsepower-hours all uses	Horsepower-hours per 1000 pounds butter*
100,000	3400	34.0
200,000	5000	25.0
300,000	6600	22.0
400,000	8150	20.7
500,000	9640	19.3
700,000	12640	18.1
Average†	6160	26.4

* It is quite probable that creameries of different outputs do not run their machines equally near to normal output, which introduces an error into this comparison. As explained in the text, the figures are also probably all too high.

† 233,000 pounds.

Table LI gives the horsepower-hour requirements of the three principal groups of creameries on the basis of power requirements. Not only do the creameries pasteurizing and using ice machines use more power, but the increase is more rapid with output. The figures in this table are only roughly accurate.

The extra power required by creameries doing some separating was not enough to show distinctly.

According to the method of calculating, the all-steam plants used 26 horsepower-hours per 1000 pounds of butter, and the electric plants 27. This difference is far within the margin of error, so that no value must be assigned to it. Accurate data could very easily reverse the figures and more. The ordinary range was from 15 to 40; but this range would have been much less if actual horsepower in place of rated horsepower at normal input could have been used. One of the lowest figures is for a plant making 450,000 pounds of butter and using 6000 horsepower-hours; one of the highest is for a creamery making 61,000 pounds and using 4000 horsepower-hours.

TABLE LI

RELATION OF OUTPUT TO POWER UTILIZATION FOR DIFFERENT COMBINATIONS

Combinations	No. of creameries	Output	Horsepower-hours per 1000 pounds output*	Additional horsepower-hours per 100,000 pounds additional output*
		Lbs.		
Ice machines and pasteurizing.......	16	324,000	35	1750
No ice machines and pasteurizing	45	196,000	26	1600
No ice machines and no pasteurizing..	22	235,000	18	1060
All combinations..............	83	233,000	26	1560

* These figures are all probably too high, as explained in the text. Also the comparison is only a rough approximation to the truth.

There were also variations due to the fact that churns and other equipment were used at different degrees of capacity or normal input in different creameries of the same or nearly the same capacity, but the method used in the survey did not permit analyzing these.

Cost per horsepower-hour.—Cost per horsepower-hour varies with the cost of the material, labor, equipment, and space entering into it, and with the utilization of these. The data on costs of material are very unsatisfactory, partly because prices are constantly changing, and partly because estimates of opening and closing inventories were untrustworthy in many cases.

Materials.—Table LII shows the amount of coal consumed in producing a horsepower-hour in all-steam plants with different outputs. About half the decrease in coal required per 1000 pounds of output is due to the decrease in horsepower-hours and half to the decrease in coal per horsepower-hour. Partly electric plants, as nearly as can be determined by the roughly approximate data available, use not quite one-third less coal per horsepower-hour. This seems like a small saving in view of the fact that the power provided by electricity averages 72.5 per cent of the total. However, Table LIII shows that the electrically equipped creameries have boilers 64 per cent as large per 1000 pounds of output as the steam plants. These boilers are fired every day to furnish the live steam needed. Bowen, in Bulletin 747 of the United States Department of Agriculture, states that 30 per cent of the heat units of coal is lost in raising steam,[22] and a considerable part of the remaining 55 per cent lost in chimneys to maintain draft, radiation and the like, is lost in electric plants as in steam plants.

TABLE LII

RELATION OF OUTPUT TO UTILIZATION OF COAL—ALL-STEAM PLANTS

Output	Coal	Coal per horsepower-hour	Coal per 1000 pounds of butter
Lbs.	Tons	Lbs.	Lbs.
100,000	64	37.6	1280
200,000	92	36.8	920
300,000	108	32.7	720
500,000	131	27.2	520
700,000	150	23.7	430
Average*	91	36.0	930

* Average 196,000 pounds for 40 all-steam plants. Plants using wood are not included.

The cost of electric power for the 48 creameries averaged 3.9 cents per horsepower-hour as computed, or $1.01 per 1000 pounds of butter. This took the place of about one-third of the coal and wood. The coal and wood cost of the all-steam plants, including freight and hauling, averaged 11.1 cents per horsepower-hour as computed, or $2.99 per 1000 of output. The cost of the electric power, if the figures given are correct, is practically equal to the one-third saving in fuel used. The cost of other materials—oil, cotton-waste, and the like—averages 18 cents per thousand. As fuel makes up 94 per cent of the cost of materials, the variations in cost of materials with output is practically as indicated in the last column of Table LII, for both the steam and the electric plants. The average cost of power materials was 11.4 cents per horsepower-hour, and $3 per thousand of output; it was $3.17 per thousand for steam plants averaging 196,000 output, and $2.89 for electric plants averaging 263,000 output.

Equipment.—The boilers were estimated to have an average life of 17 years, the engines 20 years, and the motors 10 years. The estimates were varied according to the use and present condition of the equipment. The upkeep of the boilers was estimated at $10; of the engines, $2, and of the motors, $2. The equipment cost averaged 57 cents per thousand. It is 5 cents more per thousand for electric plants than for others in spite of their larger output, partly because of the engines and boiler capacity kept in reserve, as indicated in Table LV, and partly because the electric plants were newer and were built at higher price levels. No doubt in some cases this steam equipment was originally installed to furnish all the power for the creamery, and would not be installed in a new plant.

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[22] Bowen, "The Economic Use of Fuel in Milk Plants and Creameries," p. 43.

Labor.—The labor cost is 84 cents per thousand for the steam plants, and 67 cents for the electric plants. This is partly because less time is spent in firing; and partly because of difference in output.

Space.—Figure 19 shows how boiler-room space varies with output. Space for power equipment averages 2.05 square feet per thousand in steam plants, and only 1.78 square feet per thousand in electric plants; but it is higher-priced space, because located in better and newer buildings, so that the cost is 81 cents per thousand for steam plants and 84 cents for electric plants.

Steam vs. electric power.—The total power cost of steam plants was 20.2 cents per horsepower-hour, or $5.25 per thousand of output; and for the electric plant, 18.2 cents per horsepower-hour, or $4.92 per thousand. Making allowance for the advantage of larger output, however, the steam power would have been a little cheaper in 1919-20. It is very doubtful, however, whether this would be the case in a new plant specially built and equipped to use electric power. There would be considerable savings in space, labor, and equipment in a new plant, and the fuel cost would be somewhat reduced. Were it not for the need of live steam for pasteurizing, steaming and drying cans, and the like, the electric equipment would be much the cheaper; but as long as steam must be provided, the saving from using electric power even at daylight rates is small. The arguments for using electric power are really of another sort.

The ordinary range in cost per horsepower-hour for all plants was from 10 to 30 cents, more than half of them falling between 15 and 25 cents. The average was 19.1 cents for all creameries. The lowest cost rates were for several electric plants apparently getting low rates on power and usually with no auxiliary steam-power plant. On the other hand, some of the highest cost rates were with electric plants. Some small and some large creameries had low cost rates. The extreme cases were no doubt due to over- and under-estimates of horsepower-hours.

TABLE LIII

EQUIPMENT OF STEAM AND ELECTRIC PLANTS IN RELATION TO OUTPUT

Output groups	All steam				Partly electric			
	No. in group	Average butter output	Average boiler horsepower	Average engine horsepower	No. in group	Average butter output	Average boiler horsepower	Horsepower of engines in reserve*
Under 100,000	4	82,400	20	8	3	63,300	12	8 (1)
100,000 to 200,000	13	171,000	22	10	4	142,700	15	8 (1)
200,000 to 300,000	6	229,500	24	12	7	247,600	21	12 (5)
Over 300,000	4	417,800	25	15	5	555,600	24	15 (4)
Average	27	208,000	22	12	19	277,000	19	12 (11)

* Numbers in parentheses indicate the number of plants having engines in reserve.

Cost per thousand pounds of butter.—The ordinary range in power cost per thousand pounds of butter was from $4 to $8, and the average was $5.08. The average for creameries with 100,000 pounds output is $7; for creameries with 500,000 pounds, $4.40. Under the average, power cost increases at the rate of 40 cents for each 100,000 decrease in output; over the average, at the rate of 27 cents. Thus most of the economy of power from larger output comes with the creameries under the average size. There are, however, 13 creameries with outputs under 200,000 which have power costs under $5 per thousand.

Utilization, as computed in this analysis, is a slightly more important factor in cost than cost per horsepower-hour. An increase of 10 per cent in horsepower-hours increases costs 5.1 per cent; an increase of 10 per cent in cost per horsepower-hour increases costs 4.7 per cent. If actual horsepower-hours had been used in place of rated horsepower-hours at normal input of the equipment, the ratios, as near as can be calculated after correcting as well as possible for the error of over-estimate, would have been 10.0 per cent horsepower-hours to 10.4 per cent cost; and 10.0 per cent cost per horsepower-hour to 9.6 per cent cost. Expressed another way, creameries with one more horsepower-hour per pound of butter than the average had power cost larger by 19.9 cents per thousand, instead of 19.1 cents if strictly proportional; and creameries whose power cost an extra cent per horsepower-hour, had power costs larger by 25.3 cents per thousand, instead of 26.4 if proportional. This does not mean that any creamery by increasing its horsepower-hours or costs per horsepower-hour will affect its costs in this way, but merely that comparing the creameries as they were it worked out this way.

WATER

Table LIV shows the elements of cost of water used by creameries. The $32 charged against the 71 creameries having wells is for the extra city or village water purchased by 15 of them. The equipment consists of the pump and water tank or vat. Apparently it is about as cheap to purchase water from the city or village where this is possible as to supply it from a well. The data in the table, however, are not very accurate. The average water charge paid by the 11 creameries was 64 cents per thousand of output.

Water cost was distributed arbitrarily as follows: Preparation for churning, 90 per cent; power, churning, and cleaning, each 3⅓ per cent.

TABLE LIV

ELEMENTS OF COST OF WATER—BY SOURCES OF SUPPLY

	Well and pump	City and village	Artesian wells
Number of creameries	71	11	4
Water bill	$32	$158	...
Power	78	...	...
Equipment	42	24	$17
Total cost	$152	$182	$17
Cost per thousand of output	$0.65	$0.74	$0.07

COLD STORAGE

Of the creameries whose cold storage costs were analyzed in detail, 54 store their own ice, 12 buy it from day to day, and 19 have ice machines.

The elements of cost for creameries storing their own ice are space and expense of filling the icehouse. The space is of two sorts, that for actually storing the ice, and that occupied by the refrigerator. The storage space averages 450 square feet per creamery, 3.4 square feet per 1000 pounds of output. The refrigerator space averages 123 square feet per creamery, or 0.64 square feet per 1000 pounds of output. The space cost is 58 per cent of the total cost of $434 per creamery. The average quantity of ice stored was 154 tons, or 1600 pounds per thousand of output. There seems to be a relatively small increase in storage space and quantity of ice stored with the output of the creamery. The creameries over 400,000 pounds, however, have twice as much refrigerator space as those of 100,000 pounds output.

Only 30 of the 54 creameries have separate icehouses. These average only 40 more square feet per creamery than those with built-in icehouses. Reduced to an output basis, there is no difference between them.

The cost of storing the ice is mostly labor. Practically all creameries in Minnesota hire the work done.

Of the total cost of $434 per creamery for cold storage for these 54 creameries, $182, or 42 per cent, is for the cost of storing; $69, or 16 per cent, is cost of refrigerator space; and $183, or 42 per cent, is cost of storage space.

The cost per thousand for these 54 creameries is $2.26. It is $3.47 for the 7 with less than 100,000 pounds of output, and $1.10 per thousand for the average with more than 300,000 pounds of output (averaging 429,000).

No doubt much of the ice stored by those creameries is used for other purposes or wasted. Some is sold.

The elements of cost for creameries buying their ice from day to day are space and cost of the ice. The average cost of the ice in

1919-20 was only $1 per 1000 pounds of butter. Such creameries must use their ice much more carefully than those that store their own ice. The storage space averages only 35 square feet per creamery, and the refrigerator space, 98 square feet. Three other of these creameries, however, have a large chamber formerly used for storing their own ice.

The total cost of storage for 12 creameries using this method is $296 per creamery, or $1.45 per thousand of output.

With ice machines, power and equipment are the most important items. Power was estimated on the basis of data furnished by manufacturers of ice machines. The results obtained indicate that it is about half the total cost. The average life of the ice machine was estimated at 15 years. The cost in 1920 of a machine large enough to handle 300,000 pounds of output was $3000. Interest and depreciation are therefore large items. Equipment cost is about one third of the total. The refrigerator space was 143 square feet per creamery, which is only 0.43 square feet per thousand. The space occupied by the machine averages 45 square feet per creamery.[23] The creameries using ice machines average 330,000 pounds of output.

It would appear from the figures given that the cheapest cold storage is generally obtained by creameries that are in a position to buy their ice from local icehouses, and that ice machines are most expensive of all. However, there are some other important considerations. An ice machine saves much labor in handling ice and it should furnish better refrigeration. Moreover, the costs of operating ice machines decrease rapidly with output, so that it may well be that the ice machine is the cheapest for more than 400,000 or 500,000 pounds of output. Finally, many of the creameries with ice machines are so far from a natural supply of ice that it would cost more to haul the ice than to operate an ice machine.

STORAGE OF SUPPLIES

The principal supplies usually stored are tubs, boxes, and salt. The cost of storage of supplies was therefore distributed arbitrarily equally between churning and preparation for market.

The only cost chargeable to storage of supplies is space. The labor involved in getting materials in and out of storage was charged directly to churning and preparation for market. In most cases, a large part of the space for storage was in the attic on the second floor. Such space should really be charged at the additional cost of creating and maintaining such attic space; but as such a cost could not be determined in this survey, no charge was made. The average cost given in Table VIII, amounting to 56 cents per thousand of output, is only for the space used for this purpose on the first floor. The average space set aside on the first floor, for the creameries using only the first floor for storage, was 368 square feet, which is 1.6 square feet per thousand of output. The range is from 30 square feet to more than 2000, depending principally upon the output of the creamery, the amount of additional space provided upon the second floor, the size of the building in relation to the output, and the policy of the creamery as to buying supplies in quantity. The usual amount of floor space for storage is between 200 and 600 square feet.

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[23] The data on costs of operating ice machines are so largely estimates that it is not advisable to publish them.

CLEANING

Cleaning is an important element of cost in a creamery. It represents 11.4 per cent of all the labor cost of operating a creamery, and 6.6 per cent of all the power cost. It includes cleaning of all apparatus as well as floor. Table LV shows that labor is 63.3 per cent of the cost of cleaning. The materials cost is mostly for washing powder and brushes, whose cost averaged 23.2 cents per thousand of output in 1919-20. The space requirements, averaging 40 square feet not including passageway, are for wash sinks, steam jets, occasionally a steam sterilizer or can drier, and for standing room. The $545 per creamery equals $2.34 per thousand pounds of output.

Cleaning was distributed arbitrarily, one-fifth each to Babcock testing, receiving, preparation for churning, churning, and preparation for market. The distribution might have been somewhat more accurate if part had been charged to space and distributed with space.

The cost of cleaning increases with output at the average rate of $125 for each additional 100,000 pounds. This means a decrease of 25 cents per thousand. This is mostly because labor is better utilized at cleaning in the larger creameries.

TABLE LV

ELEMENTS IN COST OF CLEANING

Elements of cost	Per creamery	
	Amount	Per cent
Power	$111	20.3
Labor	348	63.9
Water	5	0.9
Material	42	7.7
Total without space	$506	92.8
Space	39	7.2
Total with space	$545	100.0

PROCESS COSTS

In this section of the bulletin, the remainder of building and site, equipment, labor and management, and supplies and miscellaneous; and the intermediate costs, power, water, cold storage, and storage of supplies, are carried to the following process accounts: receiving, Babcock-testing, preparation for churning, churning, preparation for market, record keeping and correspondence, skimmilk and buttermilk disposal, sidelines, and hauling; and to extra space, general maintenance, and general management or overhead. General maintenance and general management are generally, in cost accounting analysis, distributed to the process costs on some arbitrary basis. To follow this practice in this case would partly obscure the variations which it is desired to examine, and would add nothing to the usefulness of the process cost totals.

The sum of these nine process costs and the three others will equal the sum of all the primary expenses.

The purpose of making the process analysis is to present in more detail the reason for the variations in cost. For example, the labor load of a creamery depends upon a large number of things such as whether Babcock testing is done daily, weekly, or monthly.

The process costs will not, however, be analyzed in this bulletin as closely as is desirable; too many estimates are involved in the division of labor, time, and power between processes. Survey data are seldom sufficiently accurate to permit close process analysis. In view of the inaccuracies in these figures, they must be taken as indicating only the general relationships between and within processes. For example, if a statement is made that power represented 34.3 per cent of churning cost, it must not be understood that it actually did, but rather that this result was obtained by the methods used in this analysis. It is impossible to repeat the statement everywhere it applies in the manuscript; hence it is made here with the hope that the reader will make the application as he goes along.

RECEIVING

Receiving represents 7.7 per cent of all creamery costs. Table LVI shows the relative importance of the elements making up receiving cost. The process is mostly a matter of labor, either in the actual receiving or in the cleaning that goes with it. The labor time of receiving averages 942 hours per creamery. Under receiving labor are included dumping, weighing, and grading the cream, taking the sample, recording the weights, steaming the cans, and part of the time spent in running in and out of the receiving room.

Receiving labor time, it would seem, should vary with the hours during which cream is received. Practice varies greatly in this matter. Of the 88 creameries, 20 receive about any time up to 4 or 6 o'clock in the afternoon, usually beginning at 7 o'clock in the morning. A few even receive in the evening, especially on Saturdays. At the other extreme are 11 which limit all their receiving to the morning hours before 9:30, 10, 10:30, or 11 o'clock. The first group, however, uses only a fifth more time for receiving than the second group, 4.8 hours per thousand as compared with 4.0. The saving from concentrating receiving within fewer hours is very apparent, however, with the larger creameries. One concludes, therefore, that it is not worth while to limit the receiving hours unless enough cream is received to keep one man busy receiving; if the man receiving has to run back and forth anyway, it takes very little longer if spread out over the whole day than if merely spread out over the forenoon. And if one person is assigned to do nothing but receive, time will be wasted unless receipts are large.

TABLE LVI

ELEMENTS IN RECEIVING COSTS

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$63	8.8	$0.27
Equipment	54	7.6	0.23
Labor	427	59.8	1.83
Power	61	8.5	0.26
Cleaning	109	15.3	0.47
Total	$714	100.0	$3.06

The group of largest creameries utilizes labor at receiving about twice as well as the group of smallest creameries. The large creameries are large partly because each patron delivers more cream. It takes nearly as long to receive a small load as a large one.

The creameries that utilize receiving time best are a few that are large and also limit their receiving time to 12 or 2 o'clock. This group reported an average of 1750 hours open for receiving, and 78 per cent of that time, or 1360 hours, actually receiving. This group used an average of only 2.7 hours per thousand pounds of output, compared with about 4.0 as the average of all creameries.

The large creameries reduce receiving costs in many cases also by using less expensive labor in the receiving room.

The power cost for the live steam used in steaming out the cans amounts to 27 cents per thousand, less than a pound of butter is worth. The extra labor and equipment required for this operation is also a small item.

Depreciation was the largest equipment item. The scale and steamer were estimated to last fifteen years and the weigh can five years.

Receiving room space averaged 95 square feet.

The decrease in receiving cost with output is at the average rate of $1.20 per 100,000 for each additional 100,000, being most rapid under 200,000 and over 400,000 and least rapid in the middle ranges.

BABCOCK TESTING

Babcock testing represents 5.1 per cent of all creamery costs, as compared with 7.7 per cent for receiving. Table LVII shows the relative importance of the elements in Babcock testing. Labor and cleaning constitute four-fifths of this cost. Cleaning is mostly labor. The labor includes, besides the actual testing, filling and labeling the bottles, and taking and recording the readings. The computations are included under record keeping. Cleaning cost is high because it includes washing both sample bottles and test bottles. Space averaged 43 square feet per creamery.

The labor cost varies mostly with output, frequency of tests, and the rate per hour. The range in hours with output is from 310, or 4.2 hours per thousand, for the group of smallest creameries, to 978, or 2.0 hours per thousand, for the group over 300,000. The larger the creamery, the larger the loads of cream delivered and the fewer samples per thousand pounds of output. Also the time of running the centrifuge is the same for a full machine as for a partly-filled one, and for a large machine as for a small one. Measuring the cream and acid and filling the test bottles, and taking and recording the readings are proportional to the number of patrons and the frequency of the tests. The 63 creameries testing daily averaged 710 hours of testing labor, or 3.3 hours per thousand. The 4 testing weekly used only half this much time; the 18 testing twice a month, only one-third this much time; and the 3 testing monthly only one-fourth this much time. The reason for this is as follows: If all patrons delivered their cream every day, there would be as many samples to test in a daily test as in a weekly or monthly test; and the saving in time from less frequent tests would tend to be proportional to the frequency of the tests. As it is, with most patrons delivering two or three times a week and some only at irregular intervals, the number of samples to be handled increases with the intervals between tests.

The labor cost also varies greatly according to whether one of the helpers or a high-salaried manager does the testing. No doubt it is highly necessary in some communities to have the most responsible man on the payroll handle the testing.

TABLE LVII

ELEMENTS IN COST OF BABCOCK-TESTING

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$30	7.0	$0.13
Equipment	15	3.1	0.06
Labor	278	57.1	1.19
Supplies	46	9.4	0.20
Power	4	0.8	0.02
Cleaning	109	22.6	0.47
Total	$482	100.0	$2.07

The cost of Babcock testing for those testing daily decreases with output at the rate of 45 cents for each 100,000 additional output; and for those testing twice per month at the rate of 12 cents for each 100,000 additional output. A small creamery testing daily has a very small lot of samples to test at a time; hence the more rapid decrease with output with daily tests.

PREPARATION FOR CHURNING

Preparation for churning begins when the cream or milk leaves the weigh stand and ends when it is ready for the churn. It includes separating whatever whole milk is received, pasteurizing the cream, propagating the starter, ripening the cream, and holding it in condition until it can be churned.

This process cost ranks third among the six processes; it represents 14.4 per cent of all creamery costs. It averages $5.76 per thousand pounds of output as compared with $6.07 per thousand for churn cost. Table LVIII shows that power, equipment, and cold storage are the most important elements of cost in preparation for churning. Power is used as belt power to drive the cream separator and to turn the coils of the pasteurizer. It is used as live steam in pasteurizing, in heating the separator milk, and in preparing the starter culture. Pasteurizing is by far the largest item. The 22 creameries not pasteurizing therefore use only a small amount of power for this process unless they receive considerable whole milk to separate.

The equipment consists of the cream separator and milk heater, when separating is done; the starter can, if starter is used; and the pasteurizer and ripener. Creameries making 200,000 pounds of butter usually have two pasteurizers and ripeners. Equipment costs for this process cost are about 50 per cent of all equipment costs. The pasteurizers were given an estimated life of 15 years; the starter cans, 15 years; and the separators, 20 years. Depreciation constitutes half the equipment cost.

TABLE LVIII

Elements of Cost in Preparation for Churning

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$117	8.7	$0.56
Equipment	68	19.9	1.16
Labor	156	11.6	0.67
Supplies	20	1.5	0.09
Power	308	22.9	1.32
Cleaning	109	8.1	0.47
Water	130	9.6	0.56
Cold storage	239	17.7	1.02
Total	$1347	100.0	$5.79

The cold storage item is large because of the large amount of ice that is used in cooling the cream after it has been pasteurized and in holding it in the desired condition; or because of the cost of keeping the ice machine running for the same purpose. Likewise, most of the cost of water must be charged to the same process.

The only materials to be charged to this process are starter culture and, in some creameries, milk powder.

The pasteurizer and ripener vats and related equipment used a good deal of floor space. To this process is charged an average of 236 square feet per creamery, almost one-fourth of the total work-room space.

Labor is a relatively small item of cost in this process. The average is 374 hours per creamery, as compared with 704 for churning, and 942 for receiving. It is more for those that pasteurize than for those that do not, and more for those that have no ice machines than for those that have.

This cost varies a great deal according to the practices of the creamery. Twenty-two do not pasteurize; 38 do not use starter culture; and 12 separate more or less milk. Hence, to analyze the variations thoroly would require a great deal of detail work, more than is justified by the accuracy of the data. Suffice to say roughly that equipment cost decreases only 20 cents per thousand for each additional 100,000 of output; that the comparable decrease in power cost is 30 cents; in cold storage cost, 25 cents; in labor hours, 70 cents; and in square feet of floor space, 20 cents. The variation with output in all the foregoing costs combined is from $9 per thousand for the group of smallest creameries to $4 for the group of largest creameries. It ranges from $2 per thousand for a creamery making 50,000 pounds which neither pasteurizes nor uses starter culture, to $12 per thousand for a creamery which does both, makes only 85,000 pounds, and has high equipment and labor costs.

CHURNING

Churning cost ranks second among the six process costs; it represents 15.1 per cent of all creamery costs. The churning operation begins with the transferring of the cream from the ripener to the churn, and ends with the butter ready to be taken from the churn. The principal component parts of the process are as follows: Starting the cream pump, rinsing the vat, adding the butter color, weighing the salt, drawing off the buttermilk, and the actual churning, washing, and butter-working operation, together with the making and recording of the salt and moisture tests. The actual churning operation requires the attention of the churn operator only part of the time.

Table LIX shows the relative importance of the various elements in churning cost. Power is, of course, the largest element. The churning operation consumes, according to the method of calculation used in this bulletin, approximately one third of all the power, both belt power and live steam, used by a creamery. Labor is the item next in importance. It represents 704 hours per creamery, or about 10 per cent of all labor and management time. Salt and butter color make the supplies cost relatively high. The churn is the most expensive single item of equipment in a creamery except the ice machine. The churn with the work space around it occupies an average of 126 square feet in the 88 creameries. The process is also charged with one half of storage space—creameries usually buy their salt in considerable quantities.

TABLE LIX

ELEMENTS IN COST OF CHURNING

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$76	5.4	$0.33
Equipment	167	11.8	0.72
Labor	307	21.7	1.32
Supplies	202	14.2	0.87
Power	486	34.3	2.08
Water	5	0.3	0.02
Cleaning	109	7.7	0.47
Storage of supplies	66	4.6	0.28
Total	$1418	100.0	$6.09

The power cost of churning for the group of creameries producing over 300,000 pounds was about half as much per thousand pounds of output as for the group with smallest output. This is partly because the larger creameries produce power more cheaply—use less coal per horsepower-hour; and partly because the larger creameries utilize churn capacity more fully. A considerable part of the power consumed by a churn with a light load is consumed by the churn itself. (See

Tables LII and LVIII.) Churn equipment is analyzed fully in the section on "Equipment Costs."

The group of smallest creameries used nearly 6 hours of labor per thousand, and the group of largest creameries, less than 3 hours per thousand. The whole range is from less than 2 to more than 8 hours per thousand. Hence output is only one of the factors. A considerable part of the labor of churning requires nearly the same time regardless of the size of the load and size of the churn; hence labor time tends to vary with the number of churn loads required per thousand of output. Smaller creameries may have churn capacity and cream volume better adjusted to each other than larger ones; but the odds are against it. Moreover, the loads are certain to be smaller.

Labor time also varies according to the extent and number and kinds of churn tests made and manufacturing records kept. Making tests and recording results are charged to churning; the computing based on these data to record keeping. The 88 creameries were put in three groups—18 which kept very meager churn records, or none at all; 44 which kept part of the records; and 28 which kept complete records. All but 10 of the creameries were equipped with both moisture- and salt-testing outfits, but some were not using both. The data show that creameries making complete tests were spending about a hundred more hours in record keeping, after differences in output were adjusted, than those keeping no churn records; but they show no effect upon churning time. The buttermakers in making these estimates may have charged all the churn record work to record keeping; or the error of the estimates may be so great as to conceal the effects expected. Such errors must be expected in survey data.

Labor cost also varies because of variations in rates of pay. Generally the highest paid employee attends to the churning.

When all costs are combined, the range is from $3.30 per thousand, for a creamery making 326,000 pounds, all of whose costs are consistently low, to over $10 per thousand, for a creamery making 100,000 pounds, with exceptionally high power and equipment costs. The variation with output is from $4.40 per thousand for the group of largest creameries, to $8.70 for the group of smallest creameries.

PREPARATION FOR MARKET

Preparation for market takes the butter as it comes from the churn, packs it, stores it, and finally delivers it on board train or to the local stores, if sold in the local market; or to customers or patrons, if sold at the creamery. It includes nailing the boxes, if boxes are used, paraffining the tubs and boxes, stamping and numbering the tubs and boxes, and weighing the butter and recording the weights. Altho the process is called "preparation for market," it includes delivering the product on board train or to customers, which may be called marketing proper. This, however, is only a small part of the total cost involved. Most of the costs of marketing proper—railway costs, commissions, etc.—are deducted from the returns received for butter sold, and hence do not appear as creamery costs.

As will appear from Table LX, over two-thirds of this cost is for supplies. Four-fifths of the $2410 for supplies is for boxes and tubs, and most of the remainder is for liners and circles, wrappers, paraffin, and drayage. The prices of tubs and boxes, liners and circles, fluctuate considerably; hence any figure as to the cost of preparation for market is not directly applicable after prices have changed. The cost of supplies in preparation for market represents 25.2 per cent of the total creamery costs, and 56.5 per cent of all supplies and miscellaneous cost.

TABLE LX

Elements in Cost of Preparation ffor Market

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$61	1.7	$0.26
Equipment	39	1.1	0.17
Labor	464	13.3	1.99
Supplies	2410	68.7	10.33
Cleaning	109	3.1	0.47
Cold storage	360	10.2	1.54
Storage of supplies	65	1.9	0.28
Total	$3514	100.0	$15.04

The next largest element of cost is labor. An average of 1178 hours per creamery is devoted to preparation for market. This may be compared with 942 hours for receiving, and 374 hours for preparation for churning. This is 16.4 per cent of all the labor and management time per creamery. It is, however, only 15.0 per cent of all labor and management cost, because more apprentice and low-priced labor is used in this process than in any other.

The next largest element in cost of preparation for market is cold storage. The temperature in the refrigerator where the butter is stored is kept at from 40 to 50 degrees F.

The equipment used consists principally of the paraffiner, butter printers, scales, box-nailing outfit, trucks, and in some cases, counter.

Different marketing policies in the different creameries to some extent affect the costs of preparation for market. Of the 88 creameries, 50 sold all their butter in New York; 16, all in Philadelphia; and 15 all in New York and other points. Only 2 sold all their butter in Chicago, 3 sold in Duluth and on the Iron Range, 1 in St. Paul, and 1 in Minneapolis.

An average of 14.8 per cent of all butter produced was sold locally, 9.1 per cent to stores and directly to consumers, and 5.7 per cent to patrons. Four creameries sold less than one per cent to patrons; and 8 over 10 per cent. Ten creameries sold no butter locally except to patrons, 8 sold less than one per cent; but on the other hand, 21 sold over 10 per cent, and 9 over 20 per cent.

An average of 81.6 per cent was packed in tubs, 15.8 per cent in boxes, and the remainder in jars for local consumption. Thirteen packed over 95 per cent of their butter in tubs, and all except 16 over 80 per cent of their butter in tubs. Only 4 packed less than half in tubs. Butter packed in boxes is for local consumption, or is shipped to Minneapolis or St. Paul or a few other local points. All the rest is packed in tubs.

The relative cost of packing in tubs and in boxes as prints will largely depend upon the relative price of tubs and liners and circles as compared with the price of boxes and wrappers. At present writing, the cost is $8.72 per thousand pounds for tubs and circles and liners, and $9.06 per thousand pounds for boxes and parchment wrappers.[24] There is also some difference in the labor involved, altho the data were not sufficiently accurate to show it clearly.

As more butter is sold locally to patrons and others, the costs of preparation for market decrease somewhat. This is because of the saving in tubs and boxes.

Preparation for market decreases less with output than any other cost, because supplies, which constitute 68.8 per cent of the total, are very nearly proportional to output. The only supply items of importance that are not, are drayage and freight on supplies. The smaller creameries also purchase in smaller quantities. For these reasons, and perhaps some others, supplies cost the group of smallest creameries about 10 per cent more than those of over 200,000 pounds. Labor, cleaning, and space, on the other hand, decrease more than half between the groups of smallest and largest creameries; and these constitute about one-fifth of this process cost. But in this case, also, most of the decrease is in creameries of less than 200,000 pounds of output. The total range with output is from $20 per thousand for the group of smallest creameries, to $15 per thousand for the group of largest creameries; but for the reasons already mentioned, over $4 of this decrease comes before 200,000 pounds.

RECORD KEEPING AND CORRESPONDENCE

In record keeping and correspondence is included the work done in the office or elsewhere by the operator, the bookkeeper, or the secretary in keeping the books of the creamery, in calculating the pounds of butterfat delivered by each patron, in making out patrons' statements and checks, in making out annual reports and income statements, and whatever computations are required for the manufacturing record; and also all correspondence with patrons, customers, receivers, railroad companies, supply houses, etc. It represents $811 per creamery, or 8.6 per cent of the total cost.

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[24] Ash tubs holding 63 pounds; 50-pound boxes. Data furnished by Creamery Package Company.

TABLE LXI

ELEMENTS IN COST OF RECORD KEEPING AND CORRESPONDENCE

	Per creamery		Per 1000 pounds of butter
	Amount	Per cent of total	
Space	$65	8.0	$0.28
Equipment	49	6.0	0.21
Labor	575	70.9	2.47
Supplies, etc.	122	15.1	0.52
Total	$811	100.0	$3.48

Table LXI shows what this $811 includes. Over 70 per cent of it is labor, which averages 1369 hours per creamery. About 5 per cent of this was used for correspondence. This 1369 hours is 19 per cent of all labor and management time.

The equipment consists of office desks, filing cases, adding machines, typewriters, safes, and, in a few cases, cash registers. Of the 88 creameries, 48 have adding machines, and 26 typewriters. Space is the whole of the office space, which averages 75 square feet per creamery.

There is a wide range in costs of record keeping and correspondence. The range with output, however, is only from $5 per thousand for the group of smallest creameries to $3 per thousand for the group of largest creameries. But in the group of 10 creameries producing less than 100,000 pounds, the range is from $1.52 to $7.50; in the group from 200,000 to 300,000 pounds, from 89 cents to $6.70; and in the group over 500,000 pounds, from 83 cents to $4.40.

The reasons for these variations are obvious. Some creameries keep better records than others. Sometimes the work is done by a buttermaker who is "slow at figures"; sometimes by an alert-minded experienced bookkeeper or secretary who knows the system he is using. Most creameries make out monthly statements, 59 in all; but 17 issue semi-monthly statements, and 12 pay for each delivery. Selling locally increases the labor of record keeping. Carrying a large sideline business increases it a very great deal.

In general, per-unit record keeping and correspondence costs are as low for the middle-sized creameries as for the largest ones. This is because the largest creameries keep more elaborate records. The rate per hour for labor of record keeping is highest in the middle group, because in such creameries most of it is done by the operator or manager, whereas the larger creameries employ special help at lower rates than the operator's. The rates per hour range from less than 30 cents in 17 creameries to more than 50 cents in 11 creameries.

GENERAL MAINTENANCE

General maintenance, averaging $274 per creamery, is made up as follows: labor and management, $50; equipment, $9; space, $12, and supplies and miscellaneous, $200. It represents the labor of the regular employees of the creamery devoted to upkeep and repair of buildings, equipment, and grounds which is not already charged to space and equipment; extra labor hired for general repair work that has not already been charged; the necessary tools for such work; work bench and work bench space; and a large assortment of miscellaneous supplies and equipment, as dippers, strainers, ladles, thermometers, paint, and lumber. Obviously, if a system of costs were being kept regularly, nearly all this expense would be charged to space and equipment and the various processes. However, as there was no real basis for distributing it with the data at hand, it was carried as a general undistributed item. It represents less than 3 per cent of all costs. It varies with output at about the same rate as labor and equipment combined.

GENERAL MANAGEMENT OR OVERHEAD

Under general management are included overhead expenses that can not be distributed between processes on any real basis. Of the total of $562 per creamery charged to this account, $261 is for the time of the regular operator or manager devoted to management. This is included in the elementary costs as labor and management. The remainder, $302, appears in the elementary costs as supplies and miscellaneous. It is divided about as follows: salaries of treasurer and directors, $89; other help hired for management, traveling expenses, etc., $50; telephone and telegraph, $35; interest on balance, $77; miscellaneous, including postage, $51.

The labor and management hours charged to general management average 506 hours per creamery, which is 7.0 per cent of the total. Eight creameries reported less than 100 hours, and 5 more than 1000 hours. The range in labor and management cost charged to this account is from 32 cents per thousand for a creamery making 112,000 pounds whose manager devoted 60 hours to management, to $3.14 per thousand for a creamery making 492,000 pounds whose manager devoted full time to management. For creameries with no helper, 6.3 per cent of labor and management is charged to general management; for creameries with one helper, 8.0 per cent; and for creameries with two or more helpers, 10.1 per cent. This is in keeping with general experience: the management of a small business can be carried on incidentally and requires very little special time, but as the business grows, there is more than a proportional amount of supervising and co-ordinating to be done. Most of the creameries making over 500,000 pounds employ a manager who does very little else. Reduced to an output basis, the range is from $1.90 per thousand in the middle-sized creameries, to $2.70 for the group of largest creameries, and to $3.20 for the group of smallest creameries.

EXTRA SPACE

Extra space, averaging $127 per creamery, is carried as a separate item because there is no proper basis for distributing it between processes; and because there is question as to whether it should be charged to current business.

BUTTERMILK AND SKIMMILK DISPOSAL

The $13 charged to buttermilk and skimmilk disposal is for equipment only. A small amount of labor and space should also be charged to this process. Equipment consists principally of buttermilk and skimmilk vats and pumps, and occasionally a weigher.

HAULING

Hauling includes only the hauling of cream. Only 12 of the 88 creameries do any hauling. This work was considered as not belonging to the creamery proper, and all receipts from it or expenses connected with it were removed from the creamery records, except this one item of equipment cost averaging $25 for the 88 creameries, which could not very well be separated. It amounts to an average of $183 for the 12 creameries.

SIDELINES

Of the 88 creameries covered in the survey, 37 did some business in sidelines. Only 5 manufactured ice cream, 2 made cottage cheese, and one made casein. The most common sideline was sweet cream and milk, bottled and sold by 14 creameries. Several more sold only cream. One was shipping buttermilk to St. Paul, and another was selling the skimmilk to a milk powder plant.

All the foregoing are dairy product sidelines. Six, however, were handling poultry and eggs, 6 more eggs alone, and 4 flour and feed. One was handling sugar, another coffee, and another a general line of groceries. Three were selling the farmers oil, and 7, salt. One was feeding skimmilk and buttermilk to hogs, one was running a laundry, and one was shipping livestock and potatoes and selling flour, feed, and farm implements.

It was of course difficult to separate the cost chargeable to sidelines. Where the sideline business was a major enterprise of a distinct sort, as in the case of the laundry or the grocery department, the creamery business was separated from the other as completely as possible. The costs given, therefore, are for clearly sideline enterprises. The average is $89 per creamery, divided as follows: labor $43, equipment $18, power $2, supplies $26. If this cost is distributed over only the creameries handling sidelines in appreciable quantity, say 22, the average is nearly $400 per creamery. When the costs per thousand pounds of butter of these 22 creameries were compared with those of the other 66, and adjustments made for differences in output, an additional cost appeared for the sideline creameries of over $2 per thousand. This would indicate that probably the $89 is too low—probably the labor item is too low. It must be remembered also that a certain amount of general management and general maintenance should be charged to sidelines.

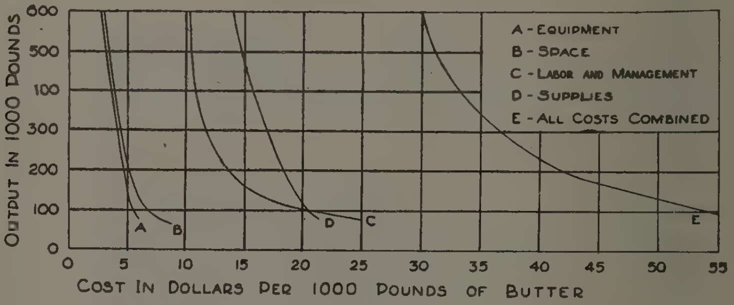

Fig. 24. Relation of Output to Creamery Cost of Butter

ALL COSTS COMBINED

Figure 24 shows the variations with output of each of the four elementary costs and of the four combined. As all four curves are drawn to the same scale, this a clear picture of the relative effect upon total cost of the variations in each of the elements. Labor and management is responsible for much more of the decrease with output than any other factor. Supplies and miscellaneous is next in significance. Labor and management shows a very pronounced effect under 200,000 pounds, and some effect above this point. Supplies and miscellaneous has its effect all the way up, altho especially at the very bottom. Space and equipment produces most pronounced effect close to the bottom. The combined effect is a curve of decreasing cost all the way up, but at a decreasing rate from the very bottom, and especially after 200,000 pounds.

The principal reasons for the shape of this combined curve may be stated as follows: (1) Labor, space, and equipment are more fully utilized by the larger creameries. There is a rapid improvement in utilization in the lower ranges. The reason for this is that there is usually a minimum-sized unit, such as one man, one churn, one engine, one ice machine, or one ripener, which is never fully utilized with a small output, and utilization improves rapidly up to the limit of this minimum-sized unit. Beyond this point utilization improves either because a second unit is more fully utilized, or the larger units permit better utilization. The larger the plant the better the fit that can be obtained between plant and volume. (2) The larger units of equipment are more economical of labor, power, and supplies than the smaller units. This is especially noticeable with coal and ice. They also occupy less floor space per unit of output. (3) The larger creameries secure their labor more cheaply because they are able to divide their work between expensive and cheap labor, whereas in the one-man creamery a high-salaried buttermaker does all the work.

It must again be made clear at this point that any given creamery with a given plant and labor force can not expect to reduce its costs with increase in output closely along the direction of this curve. This curve is based upon the kinds of plants, equipment and labor and management that are found accompanying these outputs in Minnesota. As any given creamery increases its output, it will find first one cost and then another decreasing with output up to the point of full utilization of that particular part of the equipment, or labor supply, or plant; and then as a larger unit of equipment, or an additional helper, or larger building is provided, this particular cost will be increased until the larger or additional unit is fully utilized. When it is fully utilized, the cost will be somewhat less than it was for the smaller unit when it was fully utilized. The curve for any one creamery as it increases in output is therefore likely to be an irregular jagged curve, but its general direction is much like that in Figure 24.

Moreover, if all the creameries in the state had started at 75,000 pounds output, and had gradually increased to 500,000 pounds, the cost line over which they would have traveled would have closely resembled this curve.

Output, however, is only one of the factors producing variations in cost. Table LXII shows that there is a wide range in any output group. The creamery in the highest-cost group, whose cost was 8.1 cents per pound, pays a manager $1600, a secretary $500, its directors and treasurer $120, and in addition employs a helper for two months. This is a very large payroll for a creamery making only 60,000 pounds of butter per year. In addition, its space cost is high because of the rapid depreciation of a poorly constructed concrete building. Its equipment cost is also high for a small creamery.

The creamery in the same group whose cost was 4.6 cents per pound, making 97,000 pounds of butter, pays its operator $2000; but the operator does all the work. No other salaries are paid, not even to directors. Its space cost is low—the building is of brick and was built in 1906. Its power cost is low, owing to cheap power rates.

The creamery in the second group whose cost was 6.6 cents per pound has a payroll of over $5000, altho it makes only 140,000 pounds of butter. It pays its operator $1900, its bookkeeper $300, its officers $150, and employs two full-time helpers. It has a brick building worth $12,000, and a $4000 ice machine. This creamery handles considerable milk and cream as a side line; but far from enough of these to warrant the present expansion of the plant and staff. Such a maladjustment may have arisen from a falling off in volume or from a failure of volume to meet expectations. Such maladjustments happen frequently with co-operative creameries.

In this same group are three creameries whose costs are around 3.5 cents per pound. Two of these have exceptionally low labor and management cost, paying their operators only $1450, and their secretaries $150, and employing no helpers. Two have low space cost, because they are using old frame buildings. The equipment cost is low in all three of these. None of them has an ice machine.

TABLE LXII

RANGE IN CREAMERY COSTS BY OUTPUT GROUPS

Output groups	Costs per pound of butter		
	High	Low	Average
	Cents	Cents	Cents
Under 100,000	8.1	4.6	5.75
100,000 to 150,000	6.6	3.7	5.05
150,000 to 200,000	5.2	3.5	4.31
200,000 to 250,000	4.6	3.3	4.05
250,000 to 300,000	4.1	3.3	3.77
300,000 to 400,000	3.7	2.8	3.55
400,000 to 500,000	3.4	2.6	3.20
Over 500,000	3.1	2.4	2.98
Average	8.1	2.4	4.07

The creamery in the 250,000 to 300,000 group whose cost was 4.1 cents had a large payroll with two full-time helpers, a $2000 operator, an expensive building, and high power and cold storage costs. In contrast, the low creamery in the group paid its operator $1400, a full-time helper $800, and a secretary $300. Its plant was valued at only $3000. Their equipment costs were about equal.

Two of the very largest creameries may be compared as follows: value of building, \$8000 and \$23,000; value of equipment, \$3500 and \$13,000; payroll, \$5400 and \$6000. The second of these two creameries makes nearly 150,000 pounds more butter than the first, but its costs are still 0.6 of a cent higher.

It is possible from the data thus to analyze each creamery and show why its costs are as they are. The foregoing example shows the general nature of the problem. There is not room in the bulletin for detailed analysis of individual creameries.

THE LEAST-COST COMBINATION

The various elementary costs are of course closely inter-related. A well-arranged and well-maintained plant with just the right amount of floor space can handle a larger volume with the same labor force than can a plant defective in any of these particulars. Thus building cost may to some extent be substituted for labor cost. In the same way, equipment may be to some extent substituted for labor. For example, a larger churn will mean fewer churnings—most of the churn labor is proportional to the number of churnings. Adding machines greatly reduce the labor of record keeping. Ice machines reduce very considerably the labor of preparation for churning, and electric power reduces power labor considerably. Similarly larger units of equipment are economical of space.

Thus in considerable measure labor, equipment, and space costs may be used to offset each other. But how much equipment does it pay to substitute for labor, or space for labor, or equipment for space, or vice versa? This depends upon two things, which can be stated, for example, in terms of churning: one is the number of hours of labor saved per year by the larger churn, and the number of square feet of floor space. The other is the relative prices of these cost elements—the relative prices of churns, rates of pay for labor, and costs of building space. If equipment prices rise faster than labor rates, then it will less likely pay to substitute equipment for labor.

Unfortunately the data obtained are not sufficiently accurate to warrant a careful analysis from the standpoint of the least-cost combination. Enough analysis has been made, however, to show that there is considerable variation between creameries. This means that most of them are not really working at their least-cost combination. Table VIII gives the average proportion between the four elementary costs as follows: Building and site, 11.7 per cent; equipment, 9.9 per cent; labor and management, 32.5 per cent; supplies and miscellaneous, 45.5 per cent. Table LXIII shows how these proportions change with output. In general, the proportion indicated for each output can be taken as a rough standard with which to compare any creamery with that output. Percentages for intermediate points can be obtained by dividing curve E at the desired output in Figure 24 by curves A, B, C, and D at the same output. Note that the percentage of cost in building and site decreases from the start, and that the percentage in supplies and miscellaneous increases from the start. This is because space increases less than proportionally to output, and supplies much more nearly proportionally to output. The percentage of cost in labor and management decreases rapidly at first and then increases.

TABLE LXIII

Combinations of Elementary Costs at Different Outputs

Output	Percentage of total cost				
	Equipment	Building and site	Labor and management	Supplies and miscellaneous	Total
100,000	10.3	12.5	38.9	38.3	100.0
200,000	11.3	12.2	32.5	44.0	100.0
300,000	11.0	11.9	31.3	45.8	100.0
400,000	10.5	11.5	31.9	46.1	100.0
500,000	9.9	10.6	33.1	46.4	100.0
600,000	9.1	9.8	34.2	46.9	100.0
Average	9.9	11.7	32.9	45.5	100.0

That individual creameries vary greatly from the standards in Table LXIII is illustrated by the following: There are 8 creameries in the 88 with outputs between 131,000 and 137,000 pounds. Labor and management cost plus building and site cost plus equipment cost ranges from $2581 to $6066 per creamery for these 8 creameries. Supplies and miscellaneous are omitted because fairly constant. Labor and management in these 8 creameries vary from 47 to 69 per cent of the sum of the three costs; building and site from 10 to 35 per cent; and equipment from 11 to 34 per cent. A similar showing can be made with almost any output group. A considerable part of this variation is, of course, due to differences in the age of the buildings and equipment, and the price level at the time of construction and installation. If a method of valuation could have been used, however, which would have put all plants on the same basis in these respects, there would still have been a pronounced range.

Generally speaking, however, the manager and directors of a creamery are not called upon to determine the whole of a least-cost combination at one time. The problem presents itself in such concrete forms as the following: Shall we buy another churn? How large a churn shall we buy? Shall we install an ice machine? Shall we buy an adding machine? The procedure in such cases is to estimate the cost of labor, space, and equipment in all possible combinations, make proper allowance for effect on quality of product and the like, and choose accordingly. Not all the data needed for such estimating are available; but those published in this bulletin will help considerably.

An example of the type of information needed is given in Table LXIV. After allowance was made for differences in output, increasing the floor space from 6 to 16 square feet per thousand reduced the hours per thousand by 8.2; and increasing the floor space beyond this point, as would be expected, had the opposite effect. A large amount of floor space per thousand may also indicate smaller units of equipment, and hence additional labor indirectly.

TABLE LXIV

Square feet per 1000 pounds	Hours per 1000 pounds
Less than 6	35.8
6 to 10	29.7
10 to 16	27.6
16 to 20	37.2
Over 20	47.1

The data in Table LXIV have not been analyzed closely enough to warrant any important use of them. The same is even more true of the results of several similar analyses that have not been included.

COST AND QUALITY OF PRODUCT

The ordinary range in creamery costs per pound of butter was 6 cents. The ordinary range in price received per pound of butter was 10 cents. (See Table V.) But probably 4 cents of this 10 was due to differences in quality of cream received, and 3 cents or more to differences in freight and marketing costs and seasonal variations in receipts. The rest can be ascribed to differences in skill in buttermaking, in quality of plant and equipment and the like, differences which would ordinarily be associated with differences in cost. It is the purpose of this section of the bulletin to see if high costs mean high prices for the product, and vice versa. A difference of 3 cents per pound in cost is warranted only if it means more than 3 cents more per pound for the product. This analysis is hard to make because, as just pointed out, there are three other factors besides costs which affect the price for the product. An effort will be made to allow for the differences in quality of cream. The other differences can not be properly adjusted; it is hoped, however, that they will offset each other along the range of variations in the other factors.

If costs per pound are compared directly with output regardless of the size of the creamery, the relationship obtained will be the very opposite from what one would expect, for the larger creameries not only have the lower costs, but, as will appear later, receive a better quality of cream and have better buttermakers, and hence turn out a higher quality of product. Hence it was necessary to adjust all observations for the effect of differences in output.

When per-unit labor and management costs were thus corrected, the results were as given in the second column of Table LXV. Labor costs $6 per thousand under the average for their outputs are accompanied by 2.7 cents lower prices for butter than in creameries with labor costs $2 and $4 above the average for their outputs. When, however, differences in quality of cream are eliminated, the range in effect is reduced from 0.8 cent under the average price for their grade of cream, to 0.2 cent over the average for their grade of cream. Moreover, practically all the creameries have labor costs within $—4 and $+4; and between these extremes the variation in prices received for butter from the same grade of cream is only 0.4 cent. This is only 5 per cent of the variation in labor cost. It thus appears that in general, additional labor cost, even after making allowance for difference in output, is very little associated with a better product.

TABLE LXV

Relation of Labor Cost to Prices Received for Butter

Labor costs per 1000 pounds as compared with the average for their outputs*	Average annual prices received per pound of butter	Average annual prices compared with average for their grade of cream*
	Cents	Cents
$—6	54.0	—0.8
—4	55.0	—0.2
—2	55.8	+0.2
0	56.2	+0.2
+2	56.7	+0.2
+4	56.7	+0.1
+6	56.3	+0.1

* +, above average; —, below average.

Another attack on the same problem is to compare the salaries of the head buttermakers and managers with the quality of product. The higher salaries are accompanied by higher prices for butter, but this is what one would expect, for as outputs increase, salaries also increase and concurrently the quality of the cream improves and also the quality of product even for the same grade of cream. If the advantage of this better buttermaking and better cream that accompany larger output is taken away, the quality of the butter actually decreases with salaries. Thus the buttermakers receiving from $200 to $400 over the average for creameries of their output are receiving more than a cent less per pound for their butter, and also a cent less than the average for the same grade of cream, than the buttermakers receiving from $200 to $400 less than the average for the same output. This simply means that all the effect of better salaries upon quality of product and a little more, is included in the larger-salary and better-product relationship that exists in the larger creameries.

However, in 7 creameries salaries paid buttermakers are $200 or more over the average for their outputs, and the average price for butter in 1919 was more than 58 cents a pound. Four of these receive 2 cents or more over the average price for butter made from their grade of cream. At the other extreme are several creameries with relatively low salaries and low prices. The reason that the general relationship does not run this way is that there is a larger number of creameries in which high salaries for their output are not accompanied by higher butter prices, and in which low salaries are not associated with correspondingly low butter price, for a given grade of cream.

A somewhat similar relationship exists between building costs and quality of product. The creameries with annual building costs 20 cents per square foot above the average are making appreciably better butter than those with low annual building costs. But it can not be said that the one is the cause of the other. It results because good dairy farmers will build good creameries and hire good buttermakers as well as deliver good cream. If adjustment is made for quality of cream and output, no relationship seems to be left between building cost and quality of product.

As one would expect, no obvious relationship can be traced between cost of equipment and supplies and quality of product. It may exist, but it is so slight that it can not be distinguished.

We therefore come to the conclusion that higher creamery costs, when allowance is made for output and quality of cream, have in general no very appreciable effect on the quality of the product, altho there are many individual instances in which they have. The higher creamery costs are therefore mostly for other reasons than effort to secure a better product.

COMBINATION OF GRADES OF THE COST ELEMENTS

The analysis of cost and quality of product has brought out the point that there is a tendency for certain grades of the cost factors to be associated with each other in any one creamery. Thus the quality of cream and grade of buttermaker both vary together with output.

When this relationship was examined more closely it was found that the creameries receiving "sour" cream paid their buttermakers salaries averaging $1300 per year; those receiving "fair" cream, $1700 per year; and those receiving "good" cream, $1900 per year. Annual building costs showed the same variation and about the same range. These relationships indicate that the best butter is made in the best creameries by the highest paid buttermakers. This is what would be expected. The farmers in territory with a sparse milk-cow population are not greatly interested in their income from butterfat, and will not furnish the money for an expensive creamery building. A high-salaried buttermaker would mean very high labor and management cost per thousand of output. In the dairy-farming regions, the opposite of these conditions prevail.

It is sometimes argued that the creameries receiving poor cream should have better buttermakers than those receiving good cream. Whether this is true or not depends upon whether a good buttermaker can add more to the value of poor or of good cream in manufacture, and upon output. It might be that a good buttermaker could add a half-cent per pound to the price of the product of a 50,000-pound creamery; and only a quarter-cent to the price of the product of a 300,000-pound creamery. Obviously, under these conditions the small creamery could not afford to hire the good buttermaker—it would have to bid $750 to take him away from the larger creamery, if the larger creamery knew what it was about—and he would add only $250 to the value of the butter.

Undoubtedly there are many creameries that could profitably pay a higher salary and get a better buttermaker; but there are many that could not. It would be fine, of course, if all creameries had better buttermakers; but if there is only a limited number of them, it is in the interests of all that the creameries with more and better cream should have them. In the meantime, every effort should be made to raise the general level of all buttermakers.

Also each creamery should reason out and determine the grade of buttermaker it can afford, always making proper allowance for what a good operator can do in getting the farmers to improve their cream. If enough volume can be obtained, a high-salaried buttermaker can be hired even for poor cream. Several creameries covered in the survey illustrate this.

THE MOST ECONOMICAL SIZE OF BUSINESS

Figure 24 shows that creamery costs per unit of output decrease as output increases as far as 600,000 pounds, at least. It is likely that they would continue to decrease above this point, altho at a decreasing rate.

A further consideration is quality of product. The larger creameries pay higher salaries for buttermakers and managers and secure a higher degree of skill and quality of service, which is reflected principally in higher prices for butter. Table LXVI shows that the creameries of 350,000-pound output receive cream which ranks 1.5 points better than that of creameries of 100,000-pound output; and that they made butter of it in 1919-20 which sold for 2.1 cents more per pound. If we assume the same creamery costs (4.07 cents per pound), and the same overrun (22.0 per cent), the 350,000-pound creameries could have paid 2.6 cents more per pound of butterfat; or 1.2 cents more if the grade of cream had been the same. This means that 1.4 cents of the 2.7 cents would have been due to the better cream received. If this variation with output is combined with the variation in creamery costs with output, the combined effect, assuming the same grade of cream, is 3.6 cents more paid patrons per pound of butterfat by 350,000-pound creameries, than by 100,000-pound creameries. This is stated in detail in Table LXVII. It is to be noted that the quality of product for the same grade of cream improves very slowly over 350,000 pounds of output.

TABLE LXVI

RELATION OF OUTPUT TO QUALITY OF CREAM RECEIVED AND QUALITY OF PRODUCT; 88 MINNESOTA CREAMERIES, 1919

Output	Average price received per pound of butter	Average rank* of cream received	Average price per pound of butter for same grade of cream	Price paid patrons per pound of butterfat for same grade of cream*
	Cents		Cents	Cents
50,000	53.7	3.9	54.8	61.9
100,000	54.0	3.5	54.9	62.0
150,000	54.6	3.0	55.1	62.3
200,000	55.4	2.7	55.4	62.6
250,000	55.8	2.4	55.6	62.9
300,000	56.1	2.2	55.7	63.0
350,000	56.1	2.0	55.8	63.2
400,000	56.0	2.2	55.9	63.5
500,000	55.6	2.5	56.0	63.4
600,000	55.6	2.4	56.1	63.5

* Rank 1, sweet cream; Rank 5, sour and old cream; Ranks 2, 3, and 4, intermediate grades.

† Assuming same overrun (22.0 per cent) and same creamery costs (4.07 cents) regardless of output.

For a complete statement of the economies of larger volume, this additional price for the product must therefore be combined with the savings in cost.

The problem also has another important aspect, namely, the larger the volume the greater the distance which the cream must be hauled. While this is not a creamery cost, from the standpoint of economy in organization of the whole creamery function of marketing the farmer's butterfat, it bears on the problem in exactly the same way as if the creamery were paying it.

TABLE LXVII

Relation of Output to Prices Paid Patrons for Butterfat, 88 Minnesota Creameries, 1919

Outputs	Assuming same price per pound of butter	Assuming same creamery costs per pound of butter	Combined effect per pound of butter
	Cents	Cents	Cents
50,000	58.9	61.9	58.3
100,000	61.0	62.0	60.3
150,000	62.1	62.3	61.8
200,000	62.5	62.6	62.5
250,000	62.8	62.8	63.0
300,000	63.1	63.0	63.4
350,000	63.3	63.2	63.9
400,000	63.5	63.3	64.1
500,000	63.7	63.4	64.4
600,000	63.9	63.5	64.7

The cost of hauling cream can not really be determined in any general way or with any high degree of accuracy. It will vary with the amount of butterfat produced per square mile, the number of deliveries per week, the size of the load, and above all, with the proportion of the trips that are made solely or partly for the purpose of delivering the cream. Figure 25 shows four curves of hauling costs per thousand pounds of butterfat, based on four different assumptions, as follows:

A = 4000 pounds of butterfat per square mile, 3 deliveries per week, with half of all costs of the trips, including automobile cost and labor cost, charged to cream delivery.

B = 2000 pounds of butterfat per square mile, 2 deliveries per week, with only half of the automobile cost charged to cream delivery.

C = 2000 pounds of butterfat per square mile, 2 deliveries per week, with half of all hauling costs as in A.

D = 1000 pounds of butterfat per square mile, 1 delivery per week, only half of automobile costs, as in B.

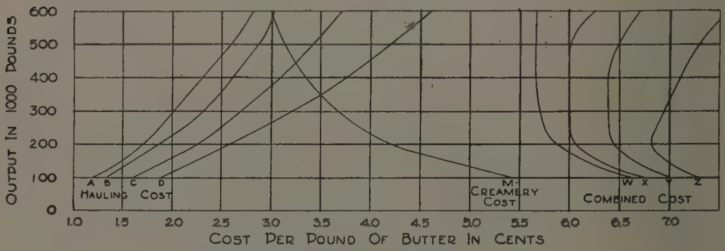

Fig. 25. Relation of Output to Creamery and Hauling Costs per Pound of Butter

In all cases, a 50-pound load of cream was assumed; and these 50 pounds of cream were assumed to be equivalent to 18 pounds of butter. Automobile costs were assumed to be 10 cents per mile. In A and C, a man-labor rate of 20 cents per hour was assumed, and a time rate of 4 minutes per mile, and 15 minutes extra at the creamery.

Assumptions B and C represent about average conditions in the state, for example, the intermediate dairy section; assumption A, conditions in the southern dairy section; and assumption D, in the Red River Valley and southeastern corn section.

Table LXVIII gives the average length of the haul, one way, and marginal length of the haul, for various outputs and for four different densities. Thus to secure 600,000 pounds of milk even at 4000 pounds of butterfat per square mile, all creamery patrons within a radius of 6.23 miles will have to deliver their milk to one creamery; and the average haul for all patrons will be twice 4.15, or 8.30 miles. At the other extreme, to secure even 100,000 pounds output with 1000 pounds of butterfat per square mile, the average haul will be 6.78 miles.

TABLE LXVIII

Length of Haul, One Way, for Different Outputs and Densities

Output	Butterfat per square mile							
	1000 pounds		2000 pounds		3000 pounds		4000 pounds	
	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal
	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles
100,000........	3.39	5.09	2.40	3.60	1.96	2.94	1.70	2.54
200,000........	4.83	7.25	3.39	5.09	2.78	4.16	2.40	3.59
300,000........	5.87	8.82	4.36	6.54	3.39	5.09	2.93	4.39
400,000........	6.79	10.17	4.82	7.23	3.92	5.87	3.39	5.08
500,000........	7.58	11.36	5.37	8.06	4.38	6.54	3.80	5.70
600,000........	8.31	12.46	5.87	8.80	4.80	7.19	4.15	6.23

Curve M in Figure 25 is the same curve of creamery costs as was given in Figure 24.

Curve W represents a combination of A and M; Curve X, of B and M; Curve Y, of C and M; and Curve Z, of D and M. Creamery costs decrease with output, but hauling costs increase. At 600,000 pounds, hauling costs are more than creamery costs for all assumptions except A. The combined cost represented by Curve W is for a density of 4000 pounds of butterfat per square mile, one-half of all hauling costs being charged to the cream. Note that this combined cost decreases to about 400,000 pounds and then remains constant to 600,000 pounds. Curve X, representing 2000 pounds of butterfat per square mile, only one half of automobile costs being charged to cream, decreases to 250,000 pounds, and remains about constant to nearly 500,000 pounds. Curve Y shows an increase at 400,000, and Curve Z promptly at 200,000 pounds.

If none of the assumptions here made fit a particular creamery, it should be possible from the data given to make some new assumptions. Density can be varied, likewise the size of the load, the butter yield of the cream, the rates for automobile hauling and for man labor, or the proportion of trips made for the sake of delivering cream. If the creamery gathers cream, the rates charged, or better still, the cost of such hauling, can be substituted for the costs in Curves A to D.

This analysis, furthermore, makes no provision for the better quality of butter made by the larger creameries. Allowance can be made for this in the diagram, however, by subtracting whatever is proper from the creamery costs as a sort of by-product credit.

It is interesting to compare Figure 25 with the data in Tables I and II. In none of the sections do the creameries average as large as would be indicated as most economical by Figure 25. There are many creameries in each section, however, which have attained this point or have gone beyond it.

TABLE LXIX

Territory Supplied by Creameries

Area	No. of creameries	Average area per creamery	Average butterfat per creamery	Butter-fat per square mile	Length of haul	
					Average	Marginal
Sq. mi.		Sq. mi.	Lbs.	Lbs.	Miles	Miles
16 to 30	8	24	135,577	5,590	1.81	2.72
31 to 60	24	45	184,425	4,163	2.53	3.76
61 to 90	26	75	190,130	2,538	3.24	4.86
91 to 120	15	104	177,961	1,715	3.80	5.70
121 to 150	8	137	212,105	1,530	4.38	6.58
151 to 180	1	168	180,486	1,074	4.89	7.24
Over 180	6	416	226,732	633	6.87	10.31
All creameries	88	96	189,600	1,941	3.71	5.56

Table LXIX shows that the average territory of the 88 creameries covered in the survey was 96 square miles, which means an average of average hauls of 3.71 miles and an average of marginal hauls of 5.56 miles. In this case, however, there is some overlapping of territory—included within the territories given are some who are hauling to neighboring creameries. It is to be noted that density of butterfat production does not alone determine the creamery area and size of creamery. There are wide variations in the size of creameries in any one density group. Thus in the group of 8 creameries serving territory from 16 to 30 square miles, are creameries ranging from 61,000 to 229,000 pounds of butterfat, and densities ranging from 2000 to 6600 pounds per square mile. The smallest area, 16 square miles, is for a creamery handling 106,000 pounds of butterfat, with a density of 6600 pounds. The largest area, 660 square miles, is for a creamery handling 330,000 pounds of butterfat, with a density of 500 pounds. Needless to say, this creamery is located in cut-over territory. The largest creamery covered in the survey serves 440 square miles of territory, with a density of 1620; but the next to the largest, only 132 square miles, with a density of 4700. The smallest creamery serves about 170 square miles of cut-over territory, with a density of about 200 pounds; the next to the smallest, only 70 square miles, with a density of 540. It thus appears that both large and small creameries are found in both densely and thinly settled territory. On the whole, the creameries are larger in the dense territory than in thin territory, but not as much so as one would expect. For example, the 11 creamery areas with densities over 5000, averaging 6300, have creameries handling an average of 282,000 pounds; and the 9 areas with densities under 1000, averaging 480, have creameries handling an average of 137,000 pounds. These circumstances demonstrate that there are other factors than density and cost of hauling which determine size of creameries.

LOCATION OF THE CREAMERY

The size of the creamery is closely related to its location. Table LXXI shows that of the 692 creameries in the state in 1920, all but 167, or 24 per cent, were located at a shipping point. Many of the 167 were located at small inland villages or cross-road trading points. Table LXX shows that only 12 of the 88 visited were in the country.

TABLE LXX

LOCATION OF CREAMERIES VISITED

Country		Village or city			
Location	No. of creameries	Population	No. of creameries		
			In center	On edge	Total
Less than 3 miles out	3	Less than 500	6	14	20
3 to 6 miles out	2	500 to 1000	8	11	19
6 to 9 miles out	6	1000 to 2000	11	10	21
Over 9 miles out	1	2000 to 3000	5	3	8
		3000 to 4000	2	0	2
		4000 and over	3	4	7
Total	12	Total	35	41	76

TABLE LXXI

LOCATION OF MINNESOTA CREAMERIES WITH RESPECT TO SHIPPING POINTS

Location	No. of creameries	Location	No. of creameries
At shipping point	525	10 miles distant	6
1 mile distant	4	11 miles distant	4
2 miles distant	4	12 miles distant	3
3 miles distant	7	13 miles distant	3
4 miles distant	13	14 miles distant	2
5 miles distant	26	15 miles distant	2
6 miles distant	29	16 miles distant	1
7 miles distant	25	20 miles distant	1
8 miles distant	21	40 miles distant	1
9 miles distant	15		
		Total	692

There are, of course, good creamery locations away from shipping points. A railway map of Minnesota shows considerable territory so far removed from railway stations that it would be expensive to haul the cream to them. It would seem much more economical under these circumstances to make the cream into butter and haul the butter to the nearest shipping point and bring back a load of coal, salt, tubs, or other supplies.

One factor in this problem is drayage costs. Table LXXII shows that drayage costs of creameries over 4 miles distant from shipping points averaged only $1.32 more per thousand pounds of butter than for creameries located within three blocks of the station. This is only a small fraction of what it would cost to haul the cream—that is, if each patron hauled his own cream.

TABLE LXXII

EFFECT OF DISTANCE FROM RAILWAY STATION ON DRAYAGE COSTS

Distance to railway station	No. of creameries at this distance	Average No. of pounds of butter made	Average drayage costs	Average drayage cost per 1000 pounds of butter
Three blocks or less	46	240,371	$165	$0.69
Three blocks to one mile	31	241,729	185	0.76
Four miles and over	11	175,193	319	2.00
All creameries visited	88	233,304	191	$0.82

Many recent developments, however, are greatly changing the situation. Farmers can deliver their cream at near-by cross-road points, and a motor truck can haul it from there to the nearest shipping-point creamery frequently at less cost to the farmer than his own longer hauls to some inland creamery. More important still, most farmers have automobiles and go to town more frequently now than formerly. In fact, many of them go so frequently that it is more economical to make whatever special trips are required for the cream alone than it is to make a special trip every few days to a creamery nearer by. Or even if it is not, they may do it anyway regardless of cost, because of the convenience or other advantage of getting to town every few days.

If, however, the creamery is located on a main-traveled road on the way to town, farmers will gladly drop off their cans on the way in; and on many days they will go no farther than the creamery. But such a creamery will get only the cream coming toward town from one direction, whereas creameries located in town obtain cream from all directions.

The result of these changes has been a steady increase in the receipts of creameries in towns, and an opposite tendency for inland creameries, with the complete disappearance of many of the latter.

Some exception must be taken to this statement for creameries at important inland trading points. Over two-thirds of the inland creameries of Minnesota received less than 100,000 pounds of butterfat, and one-eighth of them less than 50,000 pounds. There is, however, one which receives over 300,000 pounds, and 5 which receive over 200,000 pounds.

Nearly half of the creameries visited in towns were located conveniently in the center of town. Several had found it necessary to move from the edge of town to the trading district in order to meet the competition of conveniently placed centralizer cream stations. The old practice was to locate the creamery at the edge of town so as not to pollute the water of the river, creek, or lake right in the heart of the city or village. Of 102 creameries visited, 38 used the city or village sewage systems, 11 used a river, 21 a creek, 5 a lake, 4 a slough, 8 a ditch, 7 a septic tank, and 4 a cesspool. Thus with a modern sewage system, it is possible for a creamery to locate in the heart of the city. The creamery on the edge of town was frequently a "shack"; the modern creamery on main street or just off it is a brick structure as good as other structures in the same location, or better.

This makes it very clear that the location of a new creamery must be carefully considered. The future competition between motor truck and railway has a bearing upon it. It would be extremely hazardous at the present time to erect a modern brick or tile creamery anywhere except at a shipping point. The tendency toward larger output is part of the same problem.

CONCLUSION

The final test of efficiency of a creamery is the price that it pays for the butterfat in a given grade of cream. This depends upon three things—the price received for butter, the cost of manufacturing and preparation for market, and the percentage of overrun. A fourth factor, transportation and central marketing costs, is omitted in the present analysis. The three considered rank in importance about as follows: butter prices, 13; creamery costs, 8; overruns, 3.

The variations in prices received for butter are probably about one fourth due to differences in plant and equipment, operators and their helpers, and other matters of organization and management. The differences in creamery costs are also due to differences in the organization and management. It has been the purpose of this bulletin to analyze the variations in prices paid for butterfat in so far as they are due to organization, and to some extent management, especially the economic aspects of organization and management.

The results of this analysis show the major factors responsible for these variations and indicate their relative importance wherever possible. Some of these factors are subject to immediate control, others to control much more slowly, others to control only when a new plant is built, or in many cases, only when the creamery service for the whole surrounding territory is reorganized along more economical lines. Operators and managers, boards of directors, and prospective establishers of creameries can expect to make use only at this rate of the data in this bulletin in controlling the various factors affecting their costs and quality of product.

This analysis is very far from being final. Scarcely a figure in it would not be somewhat different if another 88 creameries had been selected. It is not probable, however, that the important frequency distributions and ranges would be greatly changed, or any of the major conclusions.

The authors wish again to caution the readers against placing too much reliance upon the accuracy of particular data. The data were obtained by the survey method, and altho they have been rather carefully analyzed and tested, are sure to be biased in certain respects. Particular attention is again called to three major sources of error, as follows:

1. Charging all the work done by one employee at the same rate for all processes. Thus the manager's time is charged at the same rate whether he was receiving, testing, keeping records, or actually managing.

2. Allocating power costs on the basis of rated horsepower. This affects the accuracy of the process distribution, and also of the analysis of the factors affecting power costs. Undoubtedly, also, too much dependence was placed upon the data in Bulletin 747 of the United States Department of Agriculture in making the power analysis.

3. Basing interest charges upon depreciated cost of reproduction in place of upon one half of cost of reproduction. The effect of this upon absolute cost as such is of minor consequence—it is the effect upon the analysis of factors determining cost that is the serious consideration.

It should be possible to make later studies on surer lines, now that the preliminary experimentation is done. After all, as was pointed out in the beginning, this bulletin is as much a study of methods of analysis as it is of creamery organization.

Later studies will need especially to consider a large number of details, examples of which are the following: ice machines vs. storing or buying ice; steam vs. electric power; whether to have storage for supplies on the first floor or in the attic; the relation of churn cost to size of churns, frequency of churnings, etc.; the economies of handling certain types of sidelines. Especially does the whole power analysis need to be studied more closely. Properly to analyze problems of this nature will usually require more accurate data than can be obtained by survey methods. Studies of the type of this should, therefore, be supplemented by additional studies of other types. One type of study should include the taking of careful records for a year of about fifty creameries. Another should include a large proportion of the creameries of the state on only one problem at a time, such, perhaps, as the sideline problem, or the churn-cost problem.

TECHNICAL BULLETIN 27 APRIL 1925

The University of Minnesota
Agricultural Experiment Station

Effectiveness of Calcium Cyanide in Poisoning the Pocket Gopher, Geomys bursarius (Shaw)

F. L. Washburn and C. E. Mickel
Division of Entomology and Economic Zoology

UNIVERSITY FARM, ST. PAUL

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EFFECTIVENESS OF CALCIUM CYANIDE IN POISONING THE POCKET GOPHER, *Geomys bursarius* (Shaw)

By F. L. Washburn and Clarence E. Mickel

During the last four or five years, calcium cyanide has come to be widely recommended for use in rodent control. It seems to have been used first in the extermination of the ground squirrel, *Citellus tridecemlineatus* (Mitchill); later it was reported to be effective in eradicating the black tail prairie dog, *Cynomys ludovicianus* (Ord), and it has been recommended for various species of pocket gophers. The material is sold in the form of flakes known as "calcium cyanide flakes," and also as a fine dust of various grades. Calcium cyanide flakes and calcium cyanide "A" dust have been especially recommended for use in killing pocket gophers. When this form of cyanide comes in contact with moist air or moist earth it decomposes, the products formed being hydrocyanic acid gas and hydrated lime. Hydrocyanic acid gas is, of course, highly poisonous, and when confined in the runway of a pocket gopher should produce conditions within a limited area in which no animal life can exist. If the calcium cyanide can be applied in such a way that the pocket gopher can be attracted into this area while the gas is at a killing concentration, it might be expected to be very effective.

Sanders (1921) reported successful experiments with this material in destroying a "gopher" *Citellus tridecemlineatus* (Mitchill), in Canada, altho in his account he makes the reservation that "though it may not compete economically with poisoned grain for spring use against the gopher, it should be a valuable adjunct for summer control." In laboratory experiments he found that five seconds exposure to the gas generated by calcium cyanide flakes was sufficient to cause death.

Washburn (1923), in reporting on tests with calcium cyanide in poisoning pocket gophers, states that "it appears to be very effective in loam and clay soil, but not in sandy soil."

Wade (1924) gives an account of successful experiments with calcium cyanide in exterminating the black tail prairie dog in Kansas, and in the same paper gives results of preliminary experiments made by Hisaw with the same material in poisoning pocket gophers. Wade concludes with the statement, "Preliminary experiments indicate that calcium cyanide may also be used for the destruction of pocket gophers." In the experiments reported by Wade, calcium cyanide was introduced into the main runway of the pocket gopher through openings made with a trowel, and these openings were closed after the poison had been put in the burrow. This is known as the "Kansas method."

Vaughan (1924) recommends calcium cyanide as the "outstanding remedy" for salamanders, *Geomys floridanus floridanus* (Audubon and Bachman), a species of pocket gopher inhabiting the southeastern states, altho no experimental data are cited as a basis for making such a recommendation. Vaughan advises that the new mounds of the pocket gophers be opened early in the morning by scraping away the fresh soil that has been heaped up. This will usually expose the lateral still open. The calcium cyanide is introduced into the open lateral and the opening is *not* closed. This method is known as the "Florida method."

Both Washburn (1923) and Wade (1924) indicated the need for more complete evidence upon which to base recommendations of calcium cyanide for use in eradicating pocket gophers, and it was with this in view that the authors undertook further investigations in 1924.

PRELIMINARY EXPERIMENTS

The purpose of the first two experiments, as they were first planned, was to compare the effectiveness of calcium cyanide in killing pocket gophers in sandy soil and in clay soil. While it was possible to make this comparison from the data secured, it soon developed that methods must be devised by which positive evidence could be secured that the pocket gopher was either dead or alive after the treatment. Thus, a secondary purpose of the experiments developed, that of devising means of testing the calcium cyanide so that data of this nature could be obtained.

Considerable care was used to provide the most favorable conditions for the action of the calcium cyanide. It is hardly to be expected that such conditions will obtain in the ordinary use of the material.

EXPERIMENT NO. 1

Three fields were selected for Experiment No. 1, two of light sandy soil, and one of heavy clay soil. One of the sandy fields was practically barren of vegetation, while the other was for the most part covered with sod. The clay field was cropped with a fair stand of alfalfa. The soil was moist. Pocket gophers were numerous in all three fields.

The poison was applied to the runways as follows: The main runways were located with a wire probe. A broomstick, sharpened at one end, was then used to make a hole into the runway; two ounces of calcium cyanide flakes were dropped through this hole into the main runway, and finally the hole was closed. The poison was put in the main runway and very near to fresh mounds that had been thrown up within ten hours.

After the runways had been treated with calcium cyanide, all the mounds were leveled, so that further activities of the pocket gophers, if any, could at once be located. The mounds and runways in half of each field were treated on May 13, those in the remaining half of each field were not treated.

Field in Ramsey County Infested with Pocket Gophers

The method used in this experiment is based on the assumptions: (1) that pocket gophers are active in the immediate area where they throw up new mounds; (2) that if a charge of calcium cyanide is introduced into the main burrow, with the least possible molestation of it, and the opening closed through which the charge is introduced, it will generate enough hydrocyanic acid gas to create a toxic atmosphere in the burrow in the immediate vicinity of the charge, and that when the pocket gopher in the course of his activities enters this area, he will be killed.

The effectiveness of the calcium cyanide was determined by the number of new mounds in the treated part of the field, and by comparing these with the number of new mounds in the untreated half. It was further checked by digging up the runways where no new mounds appeared and searching for the dead gopher. Several such runways were dug up for a distance of 20 feet on each side of the charge. No dead animals were found in the sandy fields, while two were found in the clay field, both within a few inches of the charge.

The fields were examined for new mounds 24 hours after applying the calcium cyanide, and again after 72 hours. Table I indicates the results of these observations.

TABLE I

Field	Runways treated	Runways in check, mounds leveled	New mounds in treated area after		New mounds in check after		Dead animals found
			24 hrs.	72 hrs.	24 hrs.	72 hrs.	
Sandy No. 1	8	6	0	0	0	0	0
Sandy No. 2	7	4	0	0	1	3	0
Clay	15	14	3	0	2	0	2

DISCUSSION

While no final conclusions with regard to the general effectiveness of calcium cyanide can be drawn from so little evidence, it is quite apparent that there was no striking difference between the results obtained on clay soil and on sandy soil. Certain other facts may be pointed out, however, which have a bearing on methods to be used in future experiments.

No new mounds appeared in the treated portions of the two sandy fields after the application of the calcium cyanide. This might be interpreted to mean that the poison was 100 per cent effective. It will be noticed, however, that no new mounds appeared in the untreated part of the same fields during the same period of observation, a fact which throws considerable doubt on such a conclusion. When several of the treated runways in these fields were dug up, no dead pocket gophers were found, a fact which is not conclusive as to the ineffectiveness of the material, but which casts some doubt on its effectiveness. In the clay field, more new mounds actually appeared in the treated part than in the untreated part, altho two dead pocket gophers were found in the former.

There is little question that if new mounds appear in close proximity to a treated runway from 24 to 72 hours after treatment, it may confidently be assumed that the occupant of the burrow has not been killed, but *if no new mounds appear near a treated runway in this time, it can not be assumed that the occupant of the runway has been killed;* for, as stated above, new mounds did not appear in either the treated or the untreated portions of the fields; and in the clay field more new mounds appeared in the treated than in the untreated portion.

As the writers wished to prove positively that the pocket gopher was either dead or alive, after a treatment of the runway with calcium cyanide, it was decided to abandon the check areas in the second experiment, and to dig up the runways more extensively in an effort to locate the dead animal.

EXPERIMENT NO. 2

The second experiment was made on June 2, in the same fields used in the previous one. The two sandy fields, however, were considered as one field. No check areas were kept. The calcium cyanide flakes were applied in the same way as before, except that the broomstick holes through which the charge was introduced were left open. In the first experiment only one charge was introduced into a single runway, but in this case, where two or three fresh mounds were found in close proximity, all connecting with the same runway, a charge was introduced near each of these new mounds, so that some runways received one charge, some two charges, and some three. The fields were examined on June 6, after 96 hours. Table II indicates the results of this experiment.

TABLE II

Field	Runways treated	Runways with			Runways with new mounds after 96 hours	Runways showing no activity after 96 hours	Dead pocket gophers found
		1 charge	2 charges	3 charges			
Sandy	12	4	5	3	2	10	1
Clay	10	4	4	2	5	5	0

DISCUSSION

The runways in which no new mounds had appeared were examined for a distance of 4 or 5 feet each side of the place where the charge was introduced, in several cases for 10 and 15 feet, and in one case for 45 feet, in order to locate, if possible, a dead pocket gopher. As indicated in the table, only one was found. It was within 5 or 6 inches of the charge of calcium cyanide.

Altho 10 runways in the sandy field and 5 in the clay field showed no further activity of the pocket gophers after 96 hours, only one dead gopher could be located. This can not be considered as conclusive evidence that all the occupants of the remaining runways were alive, but on the other hand there is no real evidence that they were killed. While it is possible that the poison gas may have killed more gophers in these two experiments than the data show, there is no positive evidence.

From the data given it will be seen that the effectiveness of the calcium cyanide was not increased by increasing the number of charges per runway, or by leaving open the holes through which the charge was applied.

Where the holes were plugged, the pocket gopher was evidently able to enter the zone where the calcium cyanide might be expected to kill, to plug up the hole, and to get away without any injurious effects, for in the examination of such runways no dead animals could be found.

In this experiment as in the first, calcium cyanide was no more effective in clay soil than in sandy soil.

FINAL EXPERIMENTS

In the final three experiments the number of runways in each was greatly increased. The material was applied according to the "Florida method" and the "Kansas mthod," and additional observations were made to determine whether the occupant of each burrow was dead or alive after the treatment. The experiments were made in a pasture of 120 acres near New Brighton, Minn., which was badly infested with pocket gophers. The soil was for the most part a sandy loam, but included small areas of clay. Applications of calcium cyanide were made on both types of soil.

EXPERIMENT NO. 3

Calcium cyanide flakes were applied according to the "Florida method," as recommended by Vaughan (1924). Very fresh mounds were scraped away, exposing the opening of the lateral, and 2 ounces of the poison were introduced into the burrow, usually at the junction of the lateral and the main runway, but in a few cases where the lateral was so long that the main runway could not be reached, the material was placed in the lateral. The opening of the lateral was *not* closed. The mounds selected were always at a considerable distance from each other, so that there was reasonable assurance that the same runway was not treated twice. The application was made on June 24 and the runways were all examined on June 25, 24 hours later. The soil was moist.

If a pocket gopher runway is opened, the animal will usually close it. In order to verify this and to compare this reaction of the pocket gophers in untreated runways with those in treated runways, approximately half of the runways were opened, but were not given a charge of calcium cyanide. The results of this experiment are:

Runways opened, but not treated	32
Runways opened and treated	34
Untreated runways closed by gopher after 24 hours	30
Untreated runways still open after 24 hours	2
Treated runways closed by gopher after 24 hours	25
Treated runways still open after 24 hours	9
Dead pocket gophers found	2

DISCUSSION

It will be noticed that the openings of all untreated runways except 2 were closed within 24 hours. This appears to be an almost universal reaction among these animals, and can be used to determine whether the animal occupying the burrow is alive.

Of the treated runways, 25 had been closed after 24 hours, indicating that the occupant had not been injured by the calcium cyanide. All these runways were opened and examined but no dead animals were found.

The 9 treated runways that remained open were examined for a short distance each side of the charge. Only 2 dead animals were found; one of these was within 2 inches of the charge, and the other about 2 feet away.

Several of the closed runways had been plugged in the main runway back of the charge of calcium cyanide, indicating that sometimes, at least, the pocket gopher plugs the main runway between himself and the charge of cyanide. Such runways appeared superficially to have remained open, and the plugging of the main runway was not discovered until a search for the dead gopher was made.

Calcium cyanide showed no greater effectiveness in this experiment than in the two previous ones.

EXPERIMENT NO. 4

The material was applied to the runways in exactly the same way, according to the "Florida method," as in the third experiment. It was realized, however, that there was a possibility that the pocket gopher might close the opening and yet be so affected by the gas generated from the calcium cyanide as to die in some other part of the burrow. If this happened it might account for the fact that only a very few dead pocket gophers were recovered after the treatments. In order to eliminate this source of possible error, all runways were treated and left open on July 10. On July 11, after 24 hours, all the burrows that had been closed were opened and left for another 24 hours. On July 12, they were examined a second time. The soil was moist. Two ounces of calcium cyanide flakes was used in each runway. The results of this experiment are summarized as follows:

Runways treated	86
Runways still open after 24 hours	18
Runways closed after 24 hours	68
Runways examined after 48 hours	78
Runways still open after 48 hours	8
Runways closed after 48 hours	70

Runways closed twice by the pocket gopher	58
Runways open after 24 hours, closed after 48 hours	12
Dead pocket gophers found	3

DISCUSSION

The most significant fact in the results is that 58, or 67 per cent, of the original 86 runways were closed twice by the pocket gophers after they had been treated with calcium cyanide, indisputable evidence that the pocket gopher was alive 48 hours after the application.

Twelve runways were closed after 48 hours that were not closed at the end of 24 hours, indicating that the occupants of these burrows were alive.

Eight runways were abandoned and not considered in the final examination after 48 hours, because cattle in the field had stepped on and caved in the main runway near the opening, making accurate observations impossible.

Only 8 runways still remained open after 48 hours.

Only 3 dead pocket gophers were found, and these were within a few inches of the charge of calcium cyanide.

There was further evidence in this experiment that the pocket gopher often plugs the main runway between the charge of calcium cyanide and himself, leaving the lateral open, which might lead one to infer that the animal had been killed.

Calcium cyanide was no more effective in killing pocket gophers in this experiment than it had been in previous ones, and effectiveness was not increased by using the "Florida method." The data of this experiment show that not more than 33 per cent could possibly have been killed, as it is certain that 67 per cent were alive 48 hours after treatment. The fact that 70 runways had been closed by the pocket gophers 48 hours after the application of the poison leads to the conclusion that 19 per cent may possibly have been killed. There is no positive evidence that more than 3½ per cent were killed.

EXPERIMENT NO. 5

Experiment No. 5 was conducted according to the "Kansas method." The laterals of the runways were opened, a charge of 2 ounces of calcium cyanide was introduced at or near the junction of the main runway and the lateral, and the opening was completely closed. This was done on September 18. On September 20 the coverings of all the openings were removed and the runways examined. All the closed runways were opened and a further examination was made on September 21. A majority of the runways were treated with 2 ounces of calcium cyanide flakes, while part of them were treated with 2 ounces of calcium cyanide "A" dust. The soil was moist. The results of this experiment are given in Table III.

TABLE III

Material used	Runways treated	Runways closed at first examination	Runways included in second examination	Runways closed at at second examination	Runways still open at second examination	Dead pocket gophers found
Calcium cyanide flakes	64	9	57	44	12	2
Calcium cyanide "A" dust ..	25	2	25	18	7	3

DISCUSSION

The "Kansas method" of applying calcium cyanide, used in this experiment, gave no better results than the "Florida method," used in the two previous experiments, and practically no better results than were obtained in the preliminary experiments. Of the 64 runways treated, 44, or 68 per cent, were closed by the pocket gophers on the second and third days after treatment with calcium cyanide flakes. Where the "A" dust was used, 72 per cent were closed on the second and third days. The highest percentage of pocket gophers that could possibly have been killed where the flakes were used is only 32 per cent, and where the "A" dust was used, only 28 per cent; and judging from the number of dead animals recovered, the cyanide did not kill more than 15 per cent.

The "A" dust was no more effective than the flakes, as can be seen from Table III.

INCIDENTAL RESULTS OF THE EXPERIMENTS

In several instances true spotted salamanders, *Amblystoma punctatum* (L.), were found dead near the charge of calcium cyanide in the pocket gopher runway.

In the fifth experiment a dead pocket gopher was recovered from a burrow on September 20, when the runways were opened and examined. This runway was left open and examined again on September 22, when it was found to be closed, indicating that it may have harbored two animals.

In the same experiment a dead pocket gopher was taken from another runway on September 20. The runway was left open and examined again on September 22, when a second was found. Either two gophers occasionally occupy the same burrow; or possibly, in these two cases, a second may have attempted to appropriate the empty runway, being successful in the first case, and failing in the second case.

In still another instance a dead striped ground squirrel, *Citellus tridecemlineatus* (Mitchill), was found in the soft earth with which the pocket gopher had closed the opening of the lateral. It may be that the ground squirrel entered the open burrow, was killed by the poison gas, and was later pushed out by the pocket gopher when it closed the opening.

COST OF APPLYING CALCIUM CYANIDE

The cost of applying calcium cyanide, based on a price of 18 cents a pound and the use of 2 ounces of the material at each runway, is 2¼ cents per runway. When the effectiveness of any material used for poisoning pocket gophers falls below 100 per cent the cost is correspondingly increased.

The cost of applying vegetable poison baits, using the poison formula "⅛ ounce strychnia alkaloid, ⅛ ounce baking soda, and 1/80 ounce saccharine," using 2 poison baits to each runway, is approximately ⅕ of a cent per runway. Vegetable poison baits have been found very effective in destroying pocket gophers by the U. S. Biological Survey, various experiment stations, and in practical work in the field.

It will readily be seen that the cost of using calcium cyanide for poisoning pocket gophers is something more than ten times as great as that of vegetable poison baits. This is a matter of considerable importance where a large number of runways are to be treated, as is often the case.

SUMMARY

1. Experiments were made with calcium cyanide to determine its effectiveness in the eradication of the pocket gopher, *Geomys bursarius* (Shaw). The calcium cyanide was applied according to methods devised by the authors, the "Florida method," and the "Kansas method." Its effectiveness on clay soil and on sandy soil was compared. The "flake" form of the material was compared with the "dust" form. Two ounces of the flakes were used in each runway in all experiments except the last, when 25 runways were treated with 2 ounces of "A" dust. Efforts were made to determine positively whether the pocket gopher was killed when the poison was introduced into the runway.

2. It was discovered that when no new mounds appeared near a runway which had been treated with calcium cyanide, it did not prove that the material had been effective in killing the animal, and that such a condition is not a safe criterion of the effectiveness of the poison.

3. It was also found that if the opening was not closed within 48 hours after a runway was treated with calcium cyanide and the lateral left open, it could not always be interpreted as meaning that the material was effective in killing the animal.

4. The pocket gopher often plugs the main runway with earth, between himself and the charge of cyanide, leaving the lateral unmolested. The plug in the main runway is not apparent and this condition might be classed as effective for the cyanide if the main runway is not examined and the true condition revealed.

5. Two positive checks were obtained on the effectiveness of calcium cyanide. Whether the pocket gophers are affected by the poison can be determined by applying the cyanide to the runway, leaving the lateral open, observing whether the lateral is closed after 24 hours, if so, reopening it, and observing if it is closed a second time after another 24 hours. If the lateral is closed twice after the application of the cyanide, it is conclusive evidence that the pocket gopher was not injured. If the lateral is closed only once it is fair, but not conclusive, evidence that the animal was not injured. If the lateral remains open for 48 hours and it can be determined that the main runway has *not* been plugged, it is fair but not conclusive evidence that the pocket gopher was killed.

6. Calcium cyanide showed no greater effectiveness on clay soil than on sandy soil. In two experiments, the effectiveness of the material was exceedingly poor on both types of soil.

7. No difference could be observed between the effectiveness of calcium cyanide flakes and "A" dust. In the experiment in which the two materials were compared, both showed little effect.

8. Several methods of applying calcium cyanide to the runway were used, no method having any advantage over the others. The calcium cyanide gave consistently poor results in all methods tried. The "Florida method" seems to offer the best opportunity for determining the effectiveness of the material.

9. In addition to its low percentage of effectiveness, calcium cyanide is much more expensive than the poison baits in general use. Leaving effectiveness out of consideration, the cost of using calcium cyanide in killing pocket gophers, at the rate of 2 ounces per runway, is about ten times that of poison vegetable baits.

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IN CO-OPERATION WITH

UNITED STATES DEPARTMENT OF AGRICULTURE,
BUREAU OF AGRICULTURAL ECONOMICS

Economic Aspects of Local Potato Warehouse Organization

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UNIVERSITY FARM, ST. PAUL

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Economic Aspects of Local Potato Warehouse Organization

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ECONOMIC ASPECTS OF LOCAL POTATO WAREHOUSE ORGANIZATION

By John D. Black, Budd A. Holt, and George M. Peterson

This bulletin deals especially with the problems of organization of local potato warehouse units as distinguished from the problems of operating and managing such units after they are set up. Of the three phases of organization, namely, economic organization, financial organization, and business organization, this bulletin considers the first. Problems of management and financial and business organization the readers will find discussed, especially from a co-operative point of view, in Minnesota Bulletin No. 195, "Local Co-operative Potato Marketing in Minnesota." The conclusions and data should be of use in planning new warehouses and reorganizing present ones upon more efficient lines.

SOURCES OF DATA

The data used in this bulletin were obtained entirely from a survey made in co-operation with the United States Department of Agriculture in the winter of 1922-23 for the year 1921. The data obtained, however, were far from being adequate for a full and accurate analysis of the problem.

The survey included 71 warehouses, classified as follows: line, 33; co-operative, 26; independent, 12.[1] These three types will be referred to hereafter in this bulletin as "line houses," "co-operatives" and "independents." The 33 line houses were owned and operated by three different wholesalers. Three warehouses operated by one company were included with the independents because their organization closely resembled that of the independents. Figure 1 shows that the survey represents a well-distributed sample of the commercial potato acreage of the state.

METHODS OF ANALYSIS

The data for each of the seventy-one warehouses were put through a separate set of cost accounts, this resulting in a set of Labor, Building and Site, Equipment, Office and Management, and Other Direct Costs per warehouse and per hundredweight of potatoes handled. These warehouse and hundredweight costs were then analyzed by statistical methods to show ranges and variations and reasons for these variations. The costs themselves are of very little significance—it is the causes of the variations and amount of effect of the different causes that are really significant. Unfortunately, as already explained, the data obtained were not sufficiently complete to make possible a very full analysis. The causes could be discovered in most cases, but their relative effects could not be accurately measured.

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[1] Five other warehouses were visited, but only part of the data needed were obtained from them.

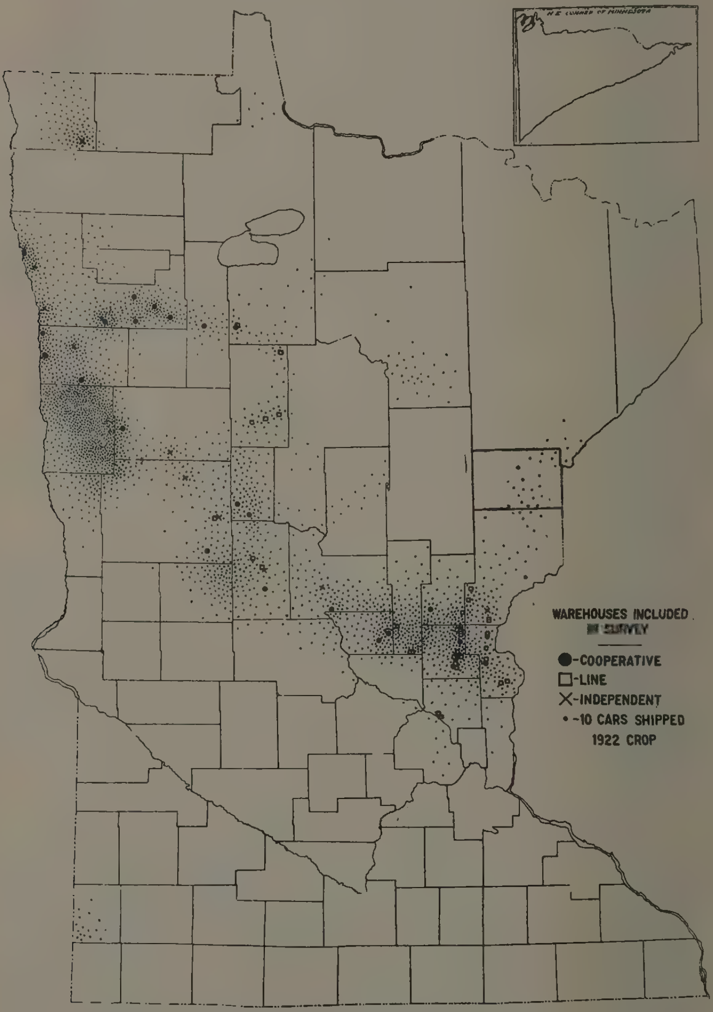

Fig. 1. Distribution of Minnesota Potato Acreage, 1922, and of Warehouses Included in the Survey

ORGANIZATION OF THE POTATO MARKET

The problems of organization of local potato warehouses are considerably affected by the organization of the potato-marketing process as a whole.

Minnesota potato production really is of two sorts, an early crop which begins coming into the market about the middle of July, and the regular main crop marketed from October to June. The early crop is produced just north and east of the Twin Cities, and is marketed in a manner somewhat different from the late crop. Part of the early crop is harvested before thoroly mature, and is trucked to the Twin Cities for immediate consumption; but a considerable quantity is loaded directly into cars and shipped to markets outside the state. The early crop is usually sorted by hand—machinery bruises immature potatoes considerably. The primary considerations for the early stock are to keep it moving, to prevent heating, and to reach market as early as possible.

The greater proportion of Minnesota potatoes, however, is of late varieties produced for winter table stock, or as in the case of the Red River Valley Early Ohio, early varieties which are harvested late to be used for southern seed stock. Marketing methods for late table stock and early seed stock are very similar. Potatoes for late winter and spring consumption or for seed must be carefully stored. If stored long they must be carefully sorted to remove the diseased or frosted tubers. No data are available as to the proportion of potatoes stored on farms, in local warehouses, and in the central market, but the local warehouses are the major factor.

Storing in the local warehouses has several advantages over storing on farms or in the terminal markets: (1) Proper storage requires protection from frost and heat, and also adequate ventilation; and few farmers have adequate facilities for these. (2) Potatoes stored on farms cannot be delivered in cold weather. Farm storage also assumes that farmers are willing to take the risk of price fluctuations and are financially able to do so.

While a certain amount of storing is necessary in terminal markets, the local warehouse has more advantages. (1) Some kind of warehouse must be provided in the local market to receive, grade, and store temporarily preparatory to shipment; and the additional cost of adding a basement to this warehouse is relatively small. (2) The decayed potatoes that develop in storage do not have to be transported when potatoes are stored locally. (3) Potatoes can be shipped directly from local to consuming centers as they are needed—saving freight and reconsignment expense. (4) Potatoes are often stored in bulk in local warehouses, and sorted and sacked only when they are to be shipped to consuming centers; whereas if they are stored in the central market, they are usually sacked in the local market, then dumped and resacked in the central market.

In the late-potato areas there may be from 1 to 15 warehouses at a shipping point. In addition to the line houses, coöperatives, and independents, large producers may have private houses.

In 1920 there were 136 co-operative warehouses in Minnesota, each owned by a local warehouse association. These associations sell their products in various ways. Some make connections with farmers' clubs, or consumers or stores in the South, or with other large direct buyers, and sell their crop direct. Others sell what they can on track to traveling buyers, and dispose of the balance to large dealers or through the regular brokerage channels. Some operate on joint account with a central wholesaler, or buy on commission for a dealer. In 1920 an attempt was made to federate these associations into one large co-operative sales agency—the Minnesota Potato Exchange. This organization failed after three years, but has been succeeded by a new organization, the Minnesota Potato Growers Exchange, now in its first year of operation. The new organization is of the non-stock centralized type. It has contracts with about 13,000 growers covering approximately 160,000 acres of potatoes and is operated on a seasonal pooling plan, and at present is selling through a national brokerage concern. Its volume of business for the first year will reach about 10,000 cars.

The independent buyers are usually of the sole-proprietorship type and operate in the town in which they live, altho occasionally an independent dealer may own and operate warehouses in two or three towns close together. The method of operation is quite similar to that of the co-operatives. As a rule, independent buyers are better informed in the matter of selling than the managers of co-operatives—their very existence depends upon the margins obtained. This is shown by the fact that they sell a greater proportion of their product direct to jobbers and large retail buyers than do the co-operatives.

The large central market wholesalers or line-house organizations have been in the past the most important agencies in the marketing of Minnesota potatoes. Their central offices are in Minneapolis and St. Paul, and they own or rent a line of country warehouses. Their chief business function is to buy potatoes in the country and ship them in carlots to a consuming center. They use their warehouses in the Twin Cities mostly for reconditioning, but to a limited extent for storing for local consumption. Their volumes of business range from less than 500 to 2500 cars annually. They all purchase potatoes in carlots from other local shippers, as well as handle the purchases made through their own warehouses. Some do a limited jobbing business in the Twin Cities, but the largest ones confine their efforts to outside shipments. Their sales are for the most part made through outside brokers or to special customers. The line houses have a decided advantage over the co-operatives and independents in the matter of selling. With a large volume of business under one general management, they are able to advertise their product, make special connections in the consuming centers, and thus sell to better advantage. Many of them have a large list of special customers upon whom they can depend for an outlet. They are also better acquainted with the trade, and are less likely to suffer losses from dealing with unreliable buyers. From their central offices in the Twin Cities, they are able to inspect all cars en route to consuming centers, and thus dispose of the various grades to the best advantage.

MEASURES OF SUCCESS

The principal measure of success of a potato warehouse is the price it is able to pay to the grower. To be sure, the owners of proprietory warehouses of the line or independent type are interested more in their margins than in the prices they pay the growers; but this is mostly only in the first instance, for unless they pay the growers reasonably well, they will not continue to receive their potatoes.

The price a warehouse is able to pay the growers depends upon the cost per hundredweight for handling potatoes and the amount and quality of service rendered. It is possible for most marketing agencies greatly to reduce their costs per unit by lowering the quality of their service, but it seldom pays to do this. Two cents per hundredweight saved by a local warehouse by hasty sorting and grading, careless loading, or reckless selling, might cost the warehouse or the growers five times that amount in prices. This bulletin is almost entirely a study of costs, quality of service being largely omitted, not because unimportant but because it is difficult to measure—in fact, is ordinarily impossible to measure it by the crude methods of survey.

Another measure of success of a local potato warehouse is the convenience of the service it offers to growers in the matter of unloading potatoes, handling the crop as fast as delivered, and providing storage if desired. It will be noted later that warehouses differ greatly in these respects and costs accordingly. No doubt much of this extra convenience and service is well worth its extra cost; but perhaps some of it is not.

No doubt, also, a local warehouse can be of considerable service to a potato-growing community in an educational way by assisting growers to obtain good seed stock, encouraging standardization of sorting methods, and the like. A warehouse organization that undertakes such a program may earn a cent or two per hundredweight in extra costs several times over.

CLASSIFICATION OF COSTS

Table I shows the classification of costs used in this analysis. It should be noted that commissions paid to brokers and exchanges, inspection fees, messenger service, demurrage charges, and other central market and transportation charges are not included, as they are not costs of a local warehouse. A further reason for not including these costs is that the records of most of the warehouses were very incomplete for such costs. For example, the account sales returned by the old Minnesota Potato Exchange did not itemize deductions in such a way as to show these various costs separately from deductions for other reasons. It is recognized, of course, that some warehouses did more direct and on-track selling than others and that for this reason, omitting central market commissions and the like, puts them on an equal basis; but as much allowance for this as possible will be made in the proper place in the analysis.

The largest item in costs is Other Direct Costs, representing 28.8 per cent of the total. This consists, however, almost entirely of sacks, tags, and twine. Office and Management represents 26.7 per cent, and Labor, 24.7 per cent.

Further discussion of what is included under each of the five elementary costs will be found under these heads later in the bulletin.

The costs given have to do with potatoes only. Only four of the warehouses handled sidelines, and it was thought best to omit all sideline costs.

The proportions which the various costs are of the total are given separately for each of the three types of warehouses. These proportions vary greatly, the reasons for which will be discussed later.

In the lower half of the table, elementary costs are represented as distributed to seven process costs, and two other items: sacks, tags, and twine; and miscellaneous. This distribution to processes is upon an arbitrary basis for the most part, and hence is not at all accurate; however, it gives a rough general impression of the relative importance of the different processes.

BUILDING AND SITE

Building and site cost, according to Table I, represents 13.1 per cent of the total local costs of potato warehouses, as compared with 24.7 per cent for labor, and 6.7 per cent for equipment. As will appear later, the range in this cost is very great, therefore it is worth while to analyze the variations very carefully.

As between building cost and site cost, the latter represents only 2.1 per cent of the two combined. Hence no further attention will be given to it.

The elements in building and site cost for the 59 warehouses which were owned by those operating them are indicated in Table II. Interest is the largest item, and depreciation next. Combined, these two represent more than two thirds of the total. These various elements of cost were determined as follows:

TABLE I

Classification of Potato Warehouse Costs by Types of Warehouses

Cost	Line (33)		Co-operative (26)		Independent (12)		All (71)	
	Per warehouse	Per cent of total	Per warehouse	Per cent of total	Per warehouse	Per cent of total	Per warehouse	Per cent of total
Elementary costs								
Labor	$696	19.2	$1512	27.0	$1940	29.5	$1205	24.7
Building and site	425	11.7	870	15.6	725	11.0	638	13.1
Equipment	209	5.8	441	7.9	412	6.3	328	6.7
Office and management	1554	42.9	966	16.2	1333	20.3	1300	26.6
Other direct costs	762	20.4	1860	33.3	2207	32.9	1409	28.9
Total	$3646	100.0	$5649	100.0	$6617	100.0	$4880	100.0
Process costs								
Buying	$544	14.9	$365	4.7	$403	6.1	$418	8.6
Receiving	90	2.5	290	5.1	288	4.3	196	4.0
Grading	338	9.3	711	12.6	666	10.1	530	10.9
Sacking	309	8.5	628	11.1	755	11.4	501	10.3
Warehousing	712	19.5	1300	23.0	1410	21.3	1046	21.4
Loading cars	144	3.9	280	5.0	365	5.5	230	4.7
Selling	819	22.5	419	7.4	660	10.0	645	13.2
Sacks, tags, and twine	678	18.6	1753	31.0	2060	31.1	1306	26.7
Miscellaneous	12	0.3	3	0.1	10	0.2	8	0.2
Total	$3646	100.0	$5649	100.0	$6617	100.0	$4880	100.0

TABLE II

Elements of Building and Site Cost, 59 Owner-Operated Warehouses

Cost	Line (26)		Co-operative (23)		Independent (10)		All (59)	
	Per warehouse	Per cent of total	Per warehouse	Per cent of total	Per warehouse	Per cent of total	Per warehouse	Per cent of total
Interest	$349	37.4	$317	39.6	$196	41.8	$276	39.1
Depreciation	339	36.3	286	35.7	157	33.6	230	35.4
Insurance	54	5.8	55	6.9	31	6.6	44	6.2
Taxes	140	15.0	96	12.0	69	14.9	102	14.4
Site rent	16	1.7	19	2.3	11	2.4	14	2.1
Miscellaneous	35	3.8	28	3.5	3	0.7	20	2.8
Total	$933	100.0	$801	100.0	$467	100.0	$706	100.0

Interest.—Interest was reckoned on the basis of original cost depreciated to date. In most cases original cost was cost of construction, but in a few cases it was the purchase price of a second-hand warehouse. The prices paid for second-hand warehouses were usually relatively low. The rate of interest used was 6 per cent, except for funds used to build or purchase which had been borrowed at other rates, as will appear later.

Depreciation.—The depreciation rate for frame buildings was usually 5 per cent, and for brick, concrete, or tile buildings, 3 or 4 per cent. It was based on cost of construction except that purchase price was used for the few buildings bought second-hand for which cost of construction could not be ascertained. As will appear later, this method of calculating depreciation introduced some undesirable variations into the results.

Insurance.—As paid.

Taxes.—As paid, not including any income taxes.

Site rent.—As paid, in most cases. Sites were usually rented from railway companies.

Miscellaneous.—Includes repair items mostly.

Fuel cost was not included with building cost because it does not vary as do building costs proper. There is no relation between variations in interest, depreciation, insurance, and taxes, and variations in fuel cost. Hence, to include fuel cost with building cost simply confuses the variations in building cost which it is desired to analyze.

Twelve warehouses were rented. The average rent paid by seven line houses was $255, by three co-operatives, $402, and by two independents, $509—an average of $334 for the twelve, which is less than half the annual cost of the owner-operated warehouses. The reason for this is partly that they are smaller, but more largely that they are located at shipping points with too many warehouses. In many cases the owners were glad to take a low rental rather than to operate them at a probable loss. The average annual building and site cost for owned and rented warehouses combined was as follows: line houses, $422; co-operatives, $871; independents, $752; all combined, $642.

METHOD OF ANALYSIS

Building cost per warehouse, under the method of calculating interest and depreciation herein used, will vary with age of building, type of construction, and size and plan of building. Building cost per hundredweight of potatoes handled will vary also with the volume of business handled, that is, with utilization. A careful analysis of building cost per hundredweight would reduce it to two factors, namely, annual cost of building per square (or cubic) foot, and hundredweight of potatoes handled per square (or cubic) foot. Thus if a given warehouse handled 10 hundredweight of potatoes per square foot of floor space, and each square foot cost 25 cents a year, its hundredweight costs are 25 cents divided by 10, or 2.5 cents. The square foot is the better unit for comparing handling capacity, and the cubic foot for handling storage capacity. Storage space is usually in the basement. Building costs for the basement and ground floor could have been roughly separated if the survey had been planned in advance on this basis. As it was not, the best that could be done was to consider all building costs on a square-foot basis.

COST PER WAREHOUSE

Under the methods used, the most important factor in annual cost per warehouse is the original cost of construction. Table III gives the range in cost of construction for fifty warehouses on this basis. These data and those following can not be used in the form here given as guides in planning warehouse construction, as they have not been adjusted for changes in price and costs of construction. This introduces a serious error, as during the period represented, costs of material and labor more than doubled. Ten of them cost less than $2000, nine $10,000 or more, and five, from $15,000 to $17,000. The fourteen frame buildings without basements cost on an average only $2584, and the twenty-three frame buildings with basements $6503. The five built of masonry (brick, concrete, or tile) without basements cost $3920, and the eight built of masonry with basements, $9529.

TABLE III

RANGE IN ORIGINAL COSTS OF 50 WAREHOUSES

Cost groups	No. in group	Average cost
Under $2000	10	$1,340
2000 to 4000	12	2,856
4000 to 6000	10	4,625
6000 to 8000	6	6,733
8000 to 10,000	3	8,619
Over 10,000	9	13,488
All	50	$5,631

Table IV gives the range in size in terms of square feet of floor space on the ground floor. The average was 2753 square feet, and the ordinary range from 1000 to 4000 square feet. Size is the most important factor in total cost, but not in unit cost.

TABLE IV

RANGE IN SIZE OF WAREHOUSES IN SQUARE FEET OF GROUND FLOOR SPACE

Size in floor space	No. in group	Average size
Square feet		Square feet
1000 to 1500	9	1297
1500 to 2000	12	1722
2000 to 2500	12	2268
2500 to 3000	7	2688
3000 to 3500	18	3234
3500 to 4000	5	3646
4000 to 4500	4	4186
4500 to 5000	2	4680
Over 5000	2	6900
All	71	2753

The frame buildings without basements averaged 2714 square feet, and cost 95 cents per square foot. The frame buildings with basements averaged 2894 square feet, and cost $2.25 per square foot. The masonry buildings without basements averaged 3144 square feet, and cost $1.25 per square foot. The masonry buildings with basements averaged 3532 square feet, and cost $2.70 per square foot. Thus the addition of basement storage added 137 per cent to the cost per square foot of frame buildings, and 116 per cent to the cost per square foot of masonry buildings. This addition is largely accounted for by the fact that the buildings with basements are of more recent construction and were built at higher cost levels. As already indicated, none of these averages is at all accurate, because they represent buildings erected at greatly differing price levels. Exactly how much of the higher costs of masonry buildings and buildings with basements and of the larger buildings is due to their being newer, cannot be stated, but undoubtedly an appreciable part of it.

TABLE V

RELATION OF CONSTRUCTION COST PER SQUARE FOOT TO DATE OF BUILDING FOR TWENTY-FIVE CO-OPERATIVE WAREHOUSES

Year of construction	No.	Average size	Average cost	Average cost per sq. ft.
		Square feet		
1916-17	4	2348	$3300	$1.47
1918	4	2775	8825	2.39
1919	5	3961	9824	2.48*
1920-21	12	2421	6456	2.67*
All	25	2774	$6652	$2.39

* Twelve of the houses built in 1919-20 were of frame construction with basements and the average cost was $2.64 per square foot.

Because of this error, it was believed unwise to try to compare the costs of brick, tile, and cement warehouses, and the effect of size and shape of building on the cost per square foot.

The average purchase price of second-hand buildings was 88 per cent of the value of new buildings of the same type depreciated to the same extent. Usually the owners of these buildings had been glad to sell them because they were unprofitable. In computing annual cost per warehouse, the original cost was divided by the estimated life to get the depreciation per year. The higher the original costs, probable life being the same, the higher the depreciation charge. Depreciation figured by this method depends upon the price level at time of construction as well as upon type of construction. Interest was based upon original cost less depreciation to date—the longer the warehouse had been built, the less its interest charge.[2] Taxes and insurance are roughly proportional to present valuation. The extreme range in annual costs per warehouse was from $90 to $2300, and the ordinary range from $200 to $1500. Table VI gives the range in detail. The ordinary range for rented warehouses was from $200 to $500.

TABLE VI

RANGE IN ANNUAL BUILDING COST PER WAREHOUSE IN RELATION TO COST PER SQUARE FOOT OF FLOOR SPACE

Cost groups	Number in group	Cost per square foot	Cost per warehouse	Square feet per warehouse
		Cents		
Under $200	8	5.5	$144	2640
200 to 400	20	12.8	287	2238
400 to 600	15	22.2	518	2335
600 to 800	10	22.7	674	2970
800 to 1000	6	32.0	901	2310
1000 to 1500	6	36.8	1240	3367
1500 and over	6	39.2	1787	4563
All	71	23.1	$642	2753

Table VII gives the comparative figures for line, independent, and co-operative warehouses. The line companies rented a larger proportion of their warehouses, and at a lower rent, than did the co-operatives or the independents. Only 18 per cent of the co-operatives were of masonry construction, as compared with 20 per cent for line houses and 25 per cent for independents. Only 67 per cent of the co-operative warehouses had basements as compared with 70 per cent of the line houses and 58 per cent of the independents. However, the co-operative and independent warehouses were much newer than the line houses, especially the co-operatives. To the extent that this is true, the lower costs shown for the line houses are misleading for reasons already given. After making allowance for this error, however, a considerable difference will remain. We shall see later whether the larger and more expensive warehouses of the co-operatives are justified by a larger volume of business.

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[2] The effect of using this method is to produce large variations in annual cost. If the sample is large enough, and representative, the average for the lot may be nearly correct; but the costs for individual warehouses unless they can be corrected for these variables will vary so much that the effects of the variations to be studied, such as those due to type of construction, size of buildings, rate of depreciation, and the like, are largely obscured. The proper method of handling interest charge for such a study is to apply the rate to one half the original cost (which gives the average investment for the life of the building), and reduce the original costs to a common price level, preferably the existing one.

TABLE VII
WAREHOUSE COSTS BY CLASSES OF ENTERPRISES

	Line	Co-operative	Independent	All
Owned buildings				
No.	26	23	10	59
Original cost	$3972	$7208	$6800	$5978
Square feet ground floor space	2829	3107	2286	2845
Original cost per square foot	$1.40	$2.32	$2.97	$2.10
Annual cost	$467	$933	$801	$705
Rented buildings				
No.	7	3	2	12
Square feet ground floor space	1971	1933	2850	2141
Rental cost	$255	$402	$509	$334
Annual cost, all buildings	$422	$871	$752	$638
Annual cost per sq. ft....	0.16	0.29	0.27	0.23

Figure 2 shows the relation between volume of business and annual cost per warehouse. For the warehouses handling 10,000 hundredweight, the annual building cost averaged around $500; for those handling 50,000 hundredweight, around $1300. Thus building cost increases much more slowly than volume of business. The reasons for this will be explained later.

ANNUAL COSTS PER SQUARE FOOT

Annual costs per warehouse must be reduced to a square-foot basis before they can be combined with data on utilization of space to give a complete explanation of variations in hundredweight costs. Table VIII shows the range in annual cost per square foot. If utilization of space were alike in all warehouses, cost per square foot alone would produce an ordinary variation of about 160 per cent of the average warehouse cost per hundredweight of potatoes handled ($0.23).[3] This table does not separate warehouses with and without basements. The ordinary range for those with basements was 10 to 60 cents; for those without basements, from 6 to 30 cents. The average for warehouses with basements is 27.2 cents; for those without basements, 14.2 cents. The average for line houses is 15.9 cents; for co-operatives, 29.4 cents; and for independents, 26.6 cents.

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[3] Partly due to error in method already explained. The range would be greatly reduced if interest and depreciation had been computed on a comparable basis.

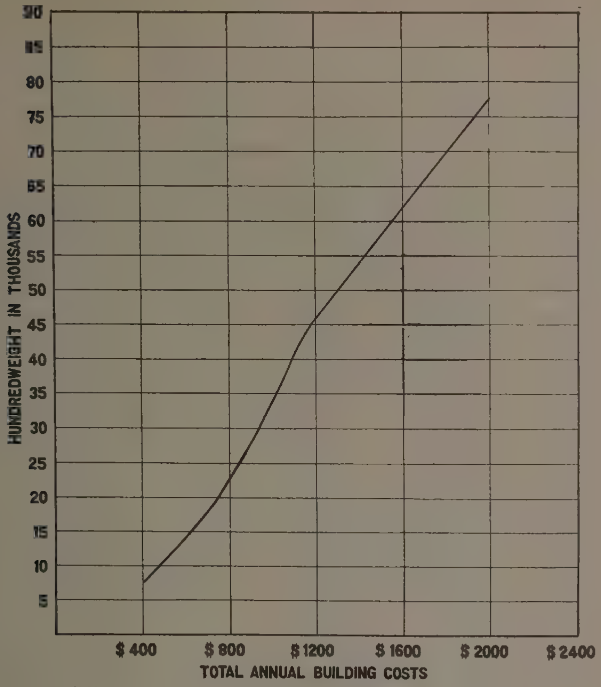

Fig. 2. Building Cost per Warehouse, Increasing with Volume of Business

TABLE VIII

Range in Annual Building Costs per Square Foot of Floor Space

Groups—cents per square foot	No. in group	Cost per square foot	Square feet per warehouse	Cost per warehouse
		Cents		
Under 10	9	5.4	3155	$171
10 to 15	13	12.1	2643	332
15 to 20	12	16.3	2584	423
20 to 30	14	24.2	2853	690
30 to 40	13	33.5	2495	837
40 to 50	9	45.9	2852	1311
Over 50	1	51.1	3600	1840
All	71	23.1	2753	638

It is interesting to note at this point a certain relation between annual building costs per square foot and volume of business. Figure 3 shows, for example, that warehouses handling only 20,000 hundredweight had costs of only 26 cents per square foot as compared with 50 cents for those handling 60,000 hundredweight. This looks peculiar at first, and is indeed largely fictitious, because the warehouses handling the larger volume of business are newer, larger, and of better construction.

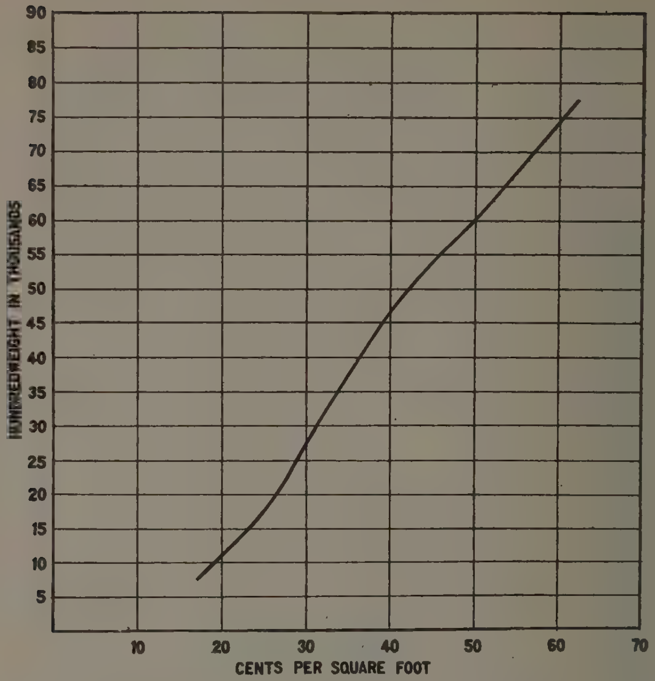

Fig. 3. Annual Building Cost per Square Foot, Increasing with Volume of Business

This increase is largely due to the fact that the larger warehouses were built more recently and at higher price levels.

UTILIZATION: HUNDREDWEIGHT PER SQUARE FOOT

Utilization of space in a warehouse is about equivalent in meaning to turnover of stock. It may be expressed either in terms of hundredweight per square foot or of square feet per hundredweight or carload. One is simply the reciprocal of the other. In this analysis it will be expressed in both ways. Table IX gives the range in size of warehouse. The range is rather wide, 8 of the houses being more than three times as large as the 21 smallest houses. Table X gives the range in volume of business handled. There were 21 at one extreme which averaged 7215 hundredweight and ten at the other extreme which averaged 57,642 hundredweight. The line houses handled less than half as many hundredweight as the co-operatives and independents. With these wide ranges in size of warehouses and volume handled, there is sure to be a very wide range in utilization, or hundredweight per square foot, as is indicated by Table XI. The best utilizations are more than five times as good as the poorest ones. Ten line houses handled less than 3 hundredweight per square foot of floor space, and

5 independents over 15 hundredweight per square foot. The range is about 175 per cent of the average.

TABLE IX

RANGE IN SIZE OF WAREHOUSES IN SQUARE FEET OF FLOOR SPACE

Groups	No. in group	Average size of group	Cost per per warehouse	Cost per square foot
Square feet				Cents
Under 1500	9	1265	$311	24.5
1500 to 2000	12	1720	448	27.0
2000 to 2500	12	2270	442	19.5
2500 to 3000	7	2690	623	23.2
3000 to 3500	18	3240	757	23.4
3500 to 4000	5	3650	938	25.7
4000 to 5000	5	4350	1060	24.3
Over 5000	3	6380	1176	18.4
All	71	2753	$637	23.1

TABLE X

RANGE IN VOLUME OF BUSINESS IN HUNDREDWEIGHTS, BY CLASSES OF WAREHOUSES

Group (000's omitted)	Line		Co-operative		Independent		All	
	No. in group	Average volume	No. in group	Average volume	No. in group	Average volume	No. in group	Average volume
		Cwt.		Cwt.		Cwt.		Cwt.
Under 10	14	7,151	5	7,631	2	6,606	21	7,215
10 to 15	10	11,767	5	11,555	2	14,164	17	11,986
15 to 20	6	17,014	4	18,326	0	0	10	17,548
20 to 40	3	23,043	6	26,408	4	29,270	13	26,512
Over 40	0	0	6	61,167	4	52,357	10	57,642
All	33	11,792	26	26,718	12	30,670	71	20,449

TABLE XI

RANGE IN UTILIZATION OF FLOOR SPACE, 71 WAREHOUSES

Hundredweight per square foot	Line	Co-operative	Independent	All combined
Under 3	10	0	0	10
3 to 6	14	10	4	28
6 to 9	3	5	1	9
9 to 12	4	4	0	8
12 to 15	2	3	2	7
15 and over	0	4	5	9
All	33	26	12	71

The average for all warehouses is 7.4 hundredweight per square foot. Table XII also compares utilization by classes of warehouses. The line houses are not only smaller, but have a much lower rate of turnover.

TABLE XII
UTILIZATION BY CLASSES OF WAREHOUSES

	Average floor space	Average volume	Utilization	
			Cwt. per sq. ft.	Sq. ft. per cwt.
	Sq. ft.	Cwt.		
Line	2639	11.792	4.5	0.22
Co-operative	2802	26.718	9.5	0.11
Independents	2866	30.670	10.7	0.09
All	2753	20.449	7.4	0.14

Figure 4 shows graphically the general relationship between volume of business and size of warehouses. Floor space on the ground floor ranges only from 2400 square feet for a volume of 7500 hundredweight, to 3280 square feet for a volume of 87,500 hundredweight.

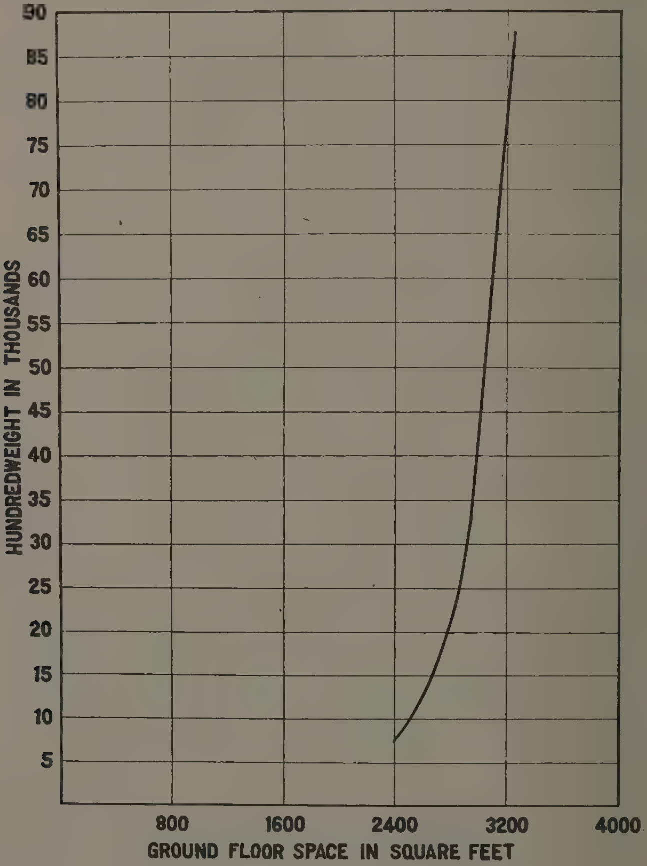

Fig. 4. Ground-Floor Space Increasing with Volume of Business

This change is only at the average rate of 110 square feet additional for each 10,000 additional volume of business. Below 20,000 the change is at the rate of 300 square feet for each additional 10,000 hundredweight in volume, but even this is a relatively small increase; in fact, only a 17 per cent increase in size for a 185 per cent increase in volume. Figure 5 shows the same data reduced to the basis of square feet per carload (360 hundredweight) of volume. At the 10,000-hundredweight volume, 90 square feet of floor space were used for each carload of output; at the 87,500-volume, 10 square feet. This is a decrease of 10.3 square feet per carload, or 18 per cent of the average, for each 10,000 increase in volume. It is thus the variations in volume handled rather than in "size of warehouses" that is principally responsible for difference in utilization. If size of building increases slowly with volume, then utilization must increase rapidly. The increase is much more rapid under 30,000 than above that point, because very few warehouses are built small enough to give good utilization with a volume under 30,000.

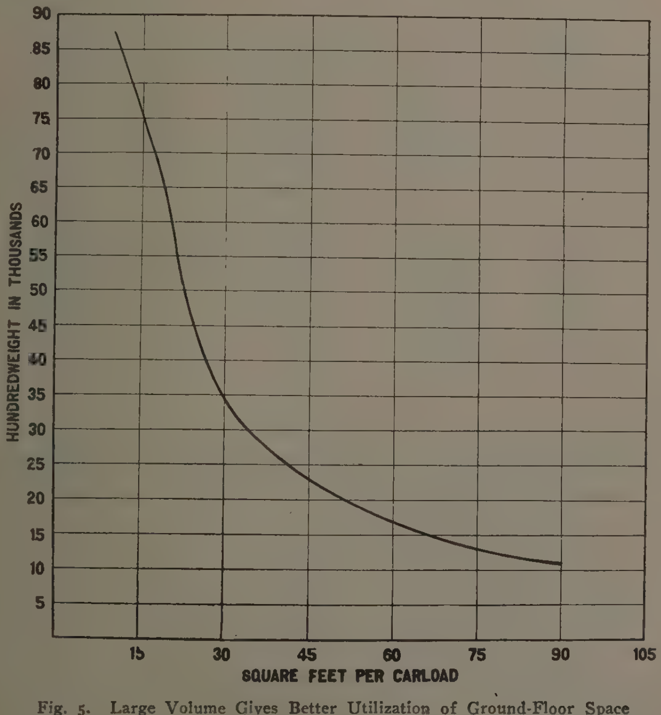

Fig. 5. Large Volume Gives Better Utilization of Ground-Floor Space

The maladjustment between volume of business and size of warehouse seems to be of two sorts: first, a large number of warehouses that were under-utilized and perhaps a few that were over-utilized—as indicated by the slow increase in size of warehouse with volume; second, wide variations in volume within each size group, as indicated in Table XIII, which gives the high and low volumes for each group. Several explanations may be offered for this maladjustment. (1) The figures on volume of business are for 1921, in which production was somewhat below normal. This will partly account for the small volume for the warehouses in general. (2) Some of the warehouses were built many years ago in areas where increased competition and changes in type of farming have decreased the volume which any warehouse can expect to obtain. This explanation especially fits the line houses, which have the poorest utilization. It is in agreement with the opinions of several of the wholesale dealers with whom the matter was discussed. Wherever, in a group of any size, a warehouse is found with very poor utilization this is likely to be the cause.

TABLE XIII

Relation of Size of Warehouse to Range in Volume

Square feet (00's omitted)	Volume of business—hundredweights							
	Co-operative		Line		Independent		All	
	High	Low	High	Low	High	Low	High	Low
10 to 15	16,881	8,071	15,954	7,314	21,240	4,500	21,240	4,500
15 to 20	11,654	5,045	24,486	4,718	8,712	8,712	24,486	4,718
20 to 25	13,580	11,160	20,571	5,025	31,040	31,040	31,040	5,025
25 to 30	41,337	21,600	16,560	7,950	37,800	37,800	41,337	7,950
30 to 35	87,205	18,324	24,073	4,499	63,360	13,329	87,205	4,499
35 to 40	64,390	11,345	9,921	9,921	44,703	44,703	64,390	9,921
40 to 45	21,670	18,332	18,051	18,031	27,000	27,000	27,000	18,031
45 to 50	63,781	63,781	10,512	10,512	.....	.....	63,781	10,512
Over 50	66,608	66,608	12,081	12,081	.....	.....	66,608	12,081
All	87,205	5,045	24,486	4,499	63,360	4,500	87,205	4,499

A third explanation is that some of the warehouses were built large to provide storage space. This is supported by the fact that in general the warehouses with basements are larger than those without basements.

The average storage capacity of line houses was 8035 hundredweight; of co-operatives, 8664 hundredweight; and of independents, 8427 hundredweight. The turnover for storage capacity was as follows: line houses, 0.69 time; co-operatives, 0.89 time; independents, 0.81 time; all combined, 0.79 time. Table XIV shows that storage capacity per square foot of floor space is almost constant for warehouses of different sizes. Therefore the warehouses with a large basement for storage have extra space on the main floor and have poorer utilization of it. Table XIV also shows that the larger warehouses have a lower turnover of storage capacity.

TABLE XIV

RELATION OF FLOOR SPACE TO STORAGE CAPACITY

Size	No. in group	Average floor space	Average storage capacity	Storage capacity per square foot of floor space
Sq. ft.		Sq. ft.	Cwt.	Cwt.
1000 to 1500	9	1265	3,780	2.98
1500 to 2000	12	1720	4,867	2.82
2000 to 2500	12	2270	6,912	3.04
2500 to 3000	7	2690	8,294	3.08
3000 to 3500	18	3240	9,792	3.02
3500 to 4000	5	3650	11,404	3.12
4000 to 4500	3	4467	13,132	2.93
4500 to 5000	2	4680	14,400	3.07
Over 5000	3	6380	21,772	3.41
All	71	2753	8,332*	3.02

* The average for the co-operatives is 8664; for the line houses, 8035; and for the independents, 8427 hundredweight.

The line houses, even tho smaller, did not utilize their storage capacity as well as did the others, because the volume of potatoes handled was so much smaller. However, the ratio of potatoes stored to potatoes handled was: line houses, 0.47; co-operatives, 0.29; independents, 0.22; and for all combined, 0.32.

COST PER HUNDREDWEIGHT

Table XV shows that the ordinary range in cost per hundredweight is from 3 to 10 cents. A comparison of Tables VIII and XI shows a wider range for utilization than for cost per square foot. Hence utilization is more responsible than cost per square foot for variations in cost per hundredweight. Furthermore, a considerable part of the variations in cost per square foot is due to using methods which did not allow for differences in date of construction. On a comparable basis, utilization would prove to be much the more important of the two factors.

TABLE XV

RANGE IN BUILDING AND SITE COST PER HUNDREDWEIGHT, BY CLASSES OF WAREHOUSES

Cost	No. in each group			
	Line	Co-operative	Independent	All
Cents				
Under 3	11	6	4	21
3 to 5	13	13	4	30
5 to 7	6	3	1	10
7 to 10	2	4	0	6
10 and over	1	..	3	4
All	33	26	12	71

In planning a new warehouse, therefore, more attention needs to be given to building the right size of warehouse than to type and cost of construction, altho both are important. It will not be possible in this analysis to go into the question of the cost of maintaining large storage capacity and the advantages of it, but these should be carefully considered. Adding a basement, of course, adds to the cost per square foot of floor space; and there also seems to be a tendency to build warehouses large in order to provide storage space, and this decreases the turnover both of floor space and of storage space.

The effect of utilization is made further apparent when the relation of volume of business to cost is studied. Figure 2, previously referred to, shows this relationship on a warehouse basis. Figure 6 shows this relationship expressed in terms of cost per hundredweight. At 10,000 hundredweight, the average cost is about 4.7 cents per hundredweight; at 20,000, around 3.7 cents; at 40,000, around 2.7 cents; and above 50,000, practically constant at 2.6 cents. Above 50,000 hundredweight, however, the curve is based on too few cases to make it very dependable. Under 50,000 hundredweight, the decrease in building and site cost is at an average rate of about 0.8 cents for each 10,000 increase in volume.

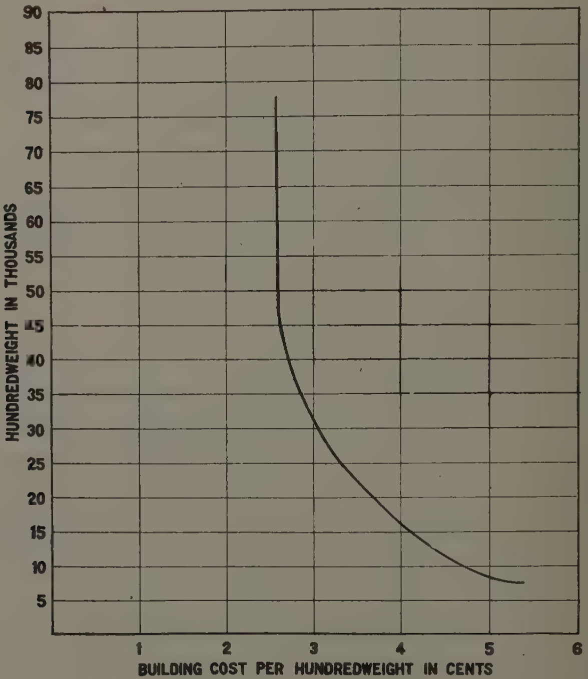

Fig. 6. Large Volume Decreases Building Costs of Handling a Hundredweight of Potatoes

It will be recognized at once that the curve in Figure 6 is a combination of the curve in Figure 3 (showing a considerable increase in costs per square foot with volume) and Figure 5 showing a very pronounced decrease in floor space used per carload.[4] The decrease in space used thus more than offsets the increases in cost per square foot under 50,000 hundredweight, and almost exactly offsets it above 50,000 hundredweight. Between 20,000 and 50,000 hundredweight, costs per square foot are about doubled, and square feet per carload are cut in four. It will be remembered that most of the increases in utilization occurred under 50,000 hundredweight.

If, as already explained, interest and depreciation had been figured in a comparable loss, a considerable part of the increase in cost per square foot with output would have disappeared. Building and site cost would then have decreased with volume more like the utilization curve in Figure 5.

Table XVI shows the relation of volume of business to cost per hundredweight, and also gives the high and low costs for each volume group. This makes it clear that altho volume of business is an important factor there are other factors of still greater importance. Thus, in the group of 17 warehouses handling less than 10,000 hundredweight, one had costs as high as 16 cents per hundredweight, and another as low as one cent. If we examine a number of individual warehouses we will probably discover some of these other causes.

TABLE XVI

RELATION OF BUILDING AND SITE COST PER HUNDREDWEIGHT TO VOLUME OF BUSINESS IN SEVENTY-ONE WAREHOUSES

Hundredweights (000's omitted)	No. in group	Building and site cost per cwt.		
		High	Low	Average
		Cents	Cents	Cents
Under 10	21	16	1	4.76
10 to 15	17	12	1	4.31
15 to 20	10	10	1	3.46
20 to 40	13	8	1	3.02
40 or over	10	4	1	2.18
All	71	16	1	3.08

No. 39, an independent handling only 40 cars, has a 36x96 hollow-tile warehouse, with basement, that cost $15,000, including a $3000 track extension. The building is about 800 square feet, or 20 square feet per carload, larger than the average for this volume of business, but the major factor is cost per square foot, which is 4.9 cents per square foot of space as compared with the average of 2.1 cents for this volume of business. The effect of the combination of high costs and poor utilization is to give building costs of 11.7 cents per hundredweight, as compared with an average of 3.08 cents for the 71 warehouses. Unless volume of business can be increased, this warehouse is too large; and probably, also, of too expensive construction. To make the latter statement, however, further information is needed, such as the certainty of potato-growing in the district, the certainty of success of the warehouse, and the attitude of the growers.

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[4] A carload was considered as 360 hundredweight. The shape of the curve is the same with carloads or hundredweights as the unit.

It should be pointed out here that high first costs do not necessarily mean high annual costs. If hollow-tile buildings last enough longer to offset the higher interest charge on the investment, then high first costs will lower the annual costs. It is always a nice point to determine what grade of construction is most profitable in the end. The more expensive the construction, the higher the interest cost and the larger the amount to divide into the life of the building; but the longer the life, the more years into which to divide it. Potato warehouses, however, tend to become obsolescent for various reasons, so that too long a period of use can not be considered with safety.

No. 55 is a line house built in 1898 of frame construction, without basement, insured for $800. It handled 30 cars at a handling cost of 0.8 cent per hundredweight.

No. 39 was a new warehouse, No. 55 an old one. If both had been built the same year, or costs had been reckoned on a comparable basis, their costs would have been much more nearly equal, but still significantly different because of differences in type of construction. Furthermore, this warehouse used only 37 square feet of floor space per carload as compared with an average of 90 for other warehouses with the same volume.

No. 30, a co-operative, has a frame warehouse 36x96 built over a cement basement, which cost $11,400. It handled 230 cars in 1921 at a building cost of 1.96 cents per hundredweight. The building cost per square foot is over twice the average, but the volume of business is so large that cost per hundredweight is relatively low.

No. 22, a co-operative warehouse which handled 112 cars in 1921, has a frame 40x80 one-story warehouse that cost $4000 in 1916. Its building costs were 1.2 cents per hundredweight, as compared with 2.7 cents for other warehouses with the same volume. Its building costs per square foot are 17.8 cents, about half the average for this volume; and its utilization, 28.6 square feet per carload, about the same as the average for the volume. The low costs are therefore due to lower costs per square foot.

Table XVII shows that line houses have the highest building costs per hundredweight, even tho their costs per square foot are very low, because of very poor utilization. Building costs of independent houses are lower than those of co-operatives because costs per square foot are lower and utilization is better.

TABLE XVII

COMPONENTS OF BUILDING AND SITE COST BY CLASSES OF WAREHOUSES

	Cost per sq. ft.	Sq. ft. per cwt.	Cost per cwt.
	Cents		Cents
Line	.16	0.23	3.61
Co-operative	.29	0.11	3.17
Independents	.28	0.09	2.45
All	.23	0.13	3.08

DISTRIBUTION OF BUILDING COSTS

Table XVIII shows how building costs are distributed to processes. This distribution is based upon estimates and measurements of the proportions and amounts of space used by the various processes. Space between articles of equipment was divided between them in whatever proportion seemed most in keeping with its actual use. In this distribution to processes, $57 of fuel cost has been included, as fuel cost is probably more nearly proportional to space used than to any other simple basis. Where potatoes are stored for considerable periods, a larger proportion, it is true, should be charged to warehousing, but this represents a degree of refinement not attempted in the rest of the analysis.

TABLE XVIII

DISTRIBUTION OF ANNUAL BUILDING COST TO PROCESSES (INCLUDING FUEL)

Process	Line		Co-operative		Independent		All warehouses	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Receiving	$ 4	1.0	$ 46	5.0	$ 17	2.1	$ 22	3.2
Grading	79	16.9	140	15.0	120	14.7	108	15.6
Sacking	65	13.9	127	13.7	118	14.6	97	13.9
Warehousing	317	68.2	618	66.3	557	68.6	468	67.3
Total	$465	100.0	$931	100.0	$812	100.0	$695	100.0

EQUIPMENT COST

Equipment cost, according to Table I, is 6.7 per cent of all costs. It is, then, one of the least important of the elementary costs. Table XIX shows the elements of equipment cost. Depreciation represents about one half the total.[5]

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[5] A more correct procedure for handling power cost would have been to set up an intermediate account called "Power," which would have included power equipment cost, power supplies cost, power labor, etc. Power cost thus constituted could be prorated on the basis of power used.

TABLE XIX

ELEMENTS OF EQUIPMENT COSTS

Process	Co-operative		Line		Independent		All warehouses	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Interest	$ 68	15.5	$ 35	16.8	$ 65	15.9	$ 52	16.0
Depreciation	210	47.7	86	41.4	210	51.0	153	46.5
Taxes	27	6.1	15	7.4	22	5.4	21	6.3
Insurance	12	2.7	8	3.7	14	3.5	10	3.2
Repairs	55	12.4	26	12.6	20	4.9	36	10.9
Power supplies	69	15.6	38	18.1	79	19.3	56	17.1
Total	$441	100.0	$208	100.0	$410	100.0	$328	100.0

Depreciation was calculated in the same way as building and site cost. This means that new warehouses have relatively higher depreciation for the same equipment because bought at higher cost levels. Interest was based, as for building and site cost, on original cost depreciated to date. It is therefore high for new warehouses for two reasons, namely, that the new equipment was higher priced, and that it had not depreciated so much. The error thus introduced seriously interferes with such correlations as that between equipment cost per hundredweight and output, and that between equipment cost and labor cost.

Equipment cost can not be analyzed to advantage as an aggregate. It is necessary to consider each item of equipment as a unit. This is best done in connection with the processes using the various items of equipment. Table XX shows the major items of equipment of a potato warehouse, and indicates how generally each is used. In addition, all warehouses are equipped with ordinary platform scales, sack-holders, shovels, and the like. Line houses are much more poorly equipped than the others with wagon dump scales and conveyers.

TABLE XX

NUMBER OF WAREHOUSES, BY CLASSES, HAVING VARIOUS ITEMS OF EQUIPMENT

	Line		Co-operative		Independent		All	
	No.	Per cent of total	No.	Per cent of total	No.	Per cent of total	No.	Per cent of total
Electric motors	23	69.7	13	50.0	6	50.0	42	59.2
Gasoline engines	6	18.2	9	34.6	4	33.3	19	26.7
Both gas and electric	4	12.1	3	11.5	2	16.6	9	12.7
Conveyors	4	12.1	7	27.0	5	41.7	16	22.5
Sack elevators	23	69.7	21	81.0	9	75.0	53	74.7
Wagon scales	4	12.1	1	3.8	0	0.0	5	7.0
Wagon dump scales	3	9.1	18	69.3	10	83.4	31	43.6
Rent wagon scales	5	15.1	1	3.9	0	0.0	6	8.5

Figures 7 and 8, showing the plans of two fairly representative potato warehouses, also indicate the placing of the equipment in each case. There are, of course, a good many variations from these plans.

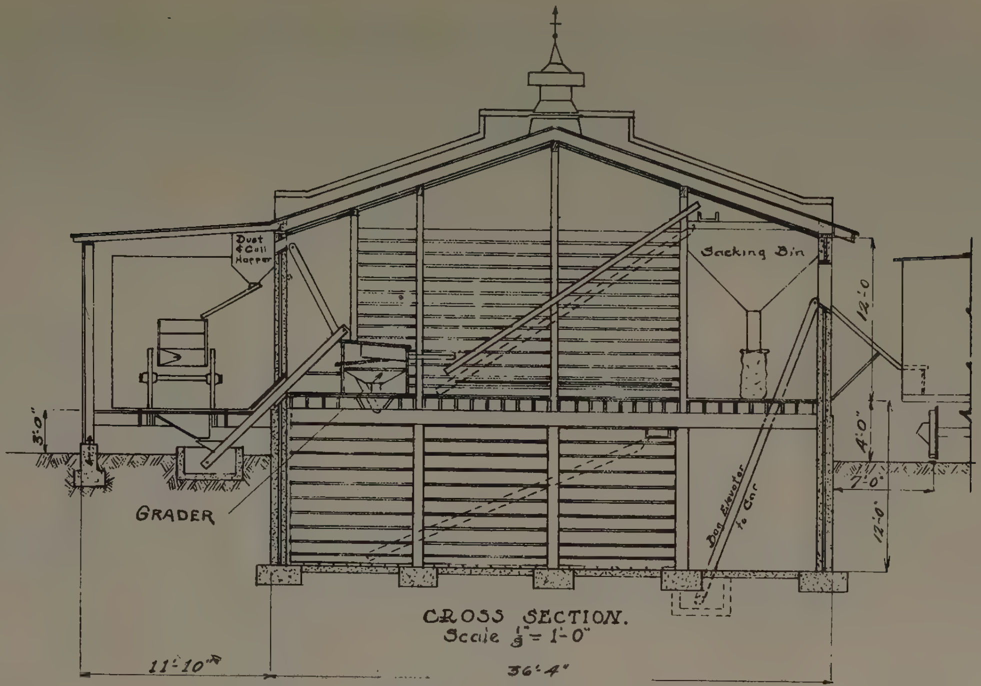

Fig. 7. Cross-Section of Typical Potato Warehouse
(Prepared by the Hickok Construction Company, Minneapolis, Minn.)

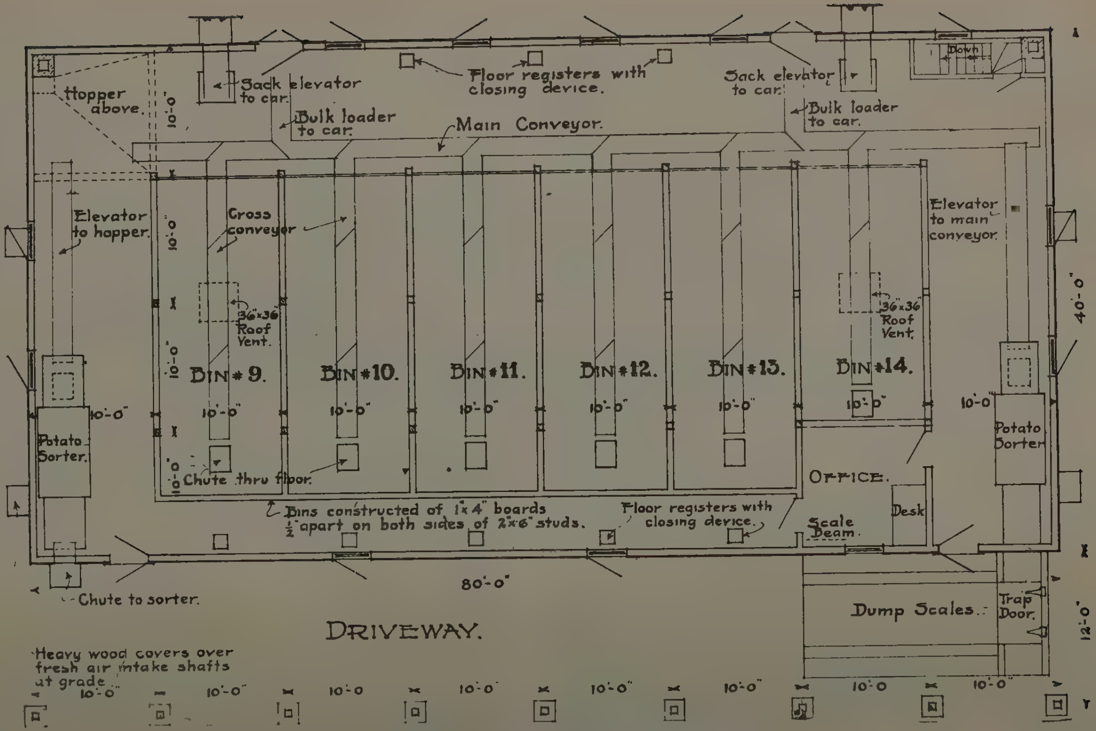

Fig. 8. First-Floor Plan of Typical Potato Warehouse

(Prepared by the Division of Agricultural Engineering, University Farm, St. Paul, Minn.)

Table XXI shows the range in value of equipment per warehouse at the time of the survey. Six of them had less than $300 worth of equipment, and ten of them more than $1500 worth. The variations are due to differences in the amount of equipment per warehouse, also in the age of the equipment, the extent to which it was depreciated at the time of the survey, and the level of prices at the time it was purchased. The average for all warehouses was $821; for line houses, $615; for co-operative houses, $976; and for independents, $1220.

TABLE XXI

RANGE IN VALUE OF EQUIPMENT BY CLASSES OF WAREHOUSES

Value of equipment	No. in group Line	Co-operative	Independent	All
Under $300	0	6	0	6
300 to 600	18	4	2	24
600 to 900	11	5	2	18
900 to 1200	3	3	4	10
1200 to 1500	0	2	1	3
1500 to 1800	0	5	1	6
1800 and over	1	1	2	4
All	33	26	12	71

These figures can not be taken as guides as to the amount which any warehouse should spend for equipment, because prices have changed; because these values are for partly depreciated equipment; and also because the average for a lot of warehouses, many of which are over-equipped or under-equipped, is no safe guide for others to follow. It is well for any warehouse operator to know, however, whether his warehouse is above or below the average, and how far.

Table XXII compares the three classes of warehouses and gives the ratios between equipment values and building values at the time of the survey. These ratios will depend upon the relative depreciation of building and equipment as well as upon amount of equipment and type of construction. The line houses have less equipment. The low ratio for co-operatives is due to the fact that more of the co-operative warehouses are of recent construction. The high ratio for independent houses is a true index of the fact that they are better equipped. The equipment of line houses is about on a par with their buildings.

TABLE XXII

VALUE OF EQUIPMENT BY CLASSES OF WAREHOUSES, RATIO OF EQUIPMENT TO BUILDING VALUE AT TIME OF SURVEY

Classes of warehouses	Value of building	Value of equipment	Ratio of equipment value to building value
			Per cent
Line	$3257	$615	18.8
Co-operative	5920	976	16.5
Independent	5583	1220	21.8
All	$4688	$821	17.5

Figure 9 shows graphically how equipment cost for warehouses varied with volume of potatoes handled for the 71 warehouses covered in the survey. Thus the small warehouses handling from 10,000 to 15,000 hundredweight had average equipment costs around $280, and the warehouses handling 50,000 hundredweight had average equipment costs of around $580. The increase with volume is rather slow under 30,000 hundredweight.

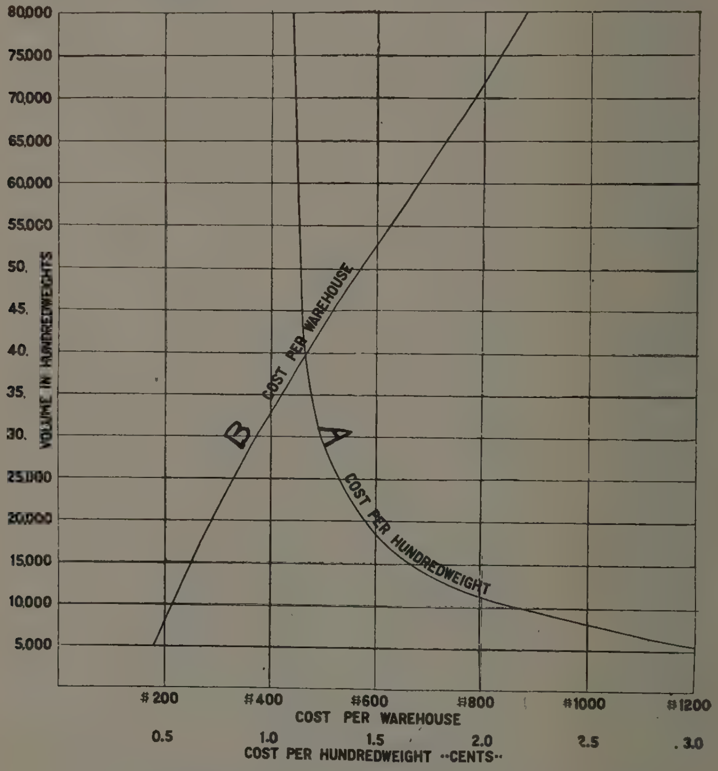

Fig. 9. Relation of Volume of Business to Equipment Costs
Curve A, Equipment Costs per Hundredweight
Curve B, Equipment Costs per Warehouse for Different Volumes

EQUIPMENT COST PER HUNDREDWEIGHT

Table XXIII shows the range when equipment cost is reduced to a hundredweight basis. The range is somewhat wider than for total warehouse equipment costs. Utilization is undoubtedly a large factor in this range, but, as already pointed out, it is not possible to show its effects separately except by analyzing each item of equipment separately, which is best undertaken in connection with the process cost analysis. Also, as with buildings, if equipment, interest, and depreciation were put on a comparable basis, utilization of equipment would prove more important than cost of equipment.

TABLE XXIII

RANGE IN ANNUAL EQUIPMENT COSTS PER HUNDREDWEIGHT BY CLASSES OF WAREHOUSES

Annual equipment cost per cwt.	No. in group			
	Line	Co-operative	Independent	All
Cents				
Under 1.0	6	4	4	14
1.0 to 1.5	8	11	3	22
1.5 to 2.0	7	1	2	10
2.0 to 3.0	8	5	2	15
3.0 to 4.0	2	3	0	5
4.0 to 5.0	1	1	1	3
5.0 and over	1	1	0	2
All	33	36	12	71

The average cost per hundredweight for all warehouses, according to Table XXIV, is 1.6 cents. In spite of high costs per warehouse, the independents have much lower costs per hundredweight. This means that, as a whole, the extra volume of business warranted their more complete equipment on the score of costs alone, to say nothing about possible saving in labor costs and greater convenience of the patrons. There were individual warehouses, however, as the two handling between 10,000 and 15,000 hundredweight, for which this was not the case. The line houses handled so small a volume of business that even their low equipment costs per warehouse left them with the highest hundredweight costs of any group. It is altogether possible that in some cases more complete and more convenient equipment might have increased their volume enough actually to reduce their per hundredweight costs.

TABLE XXIV

EQUIPMENT COSTS PER HUNDREDWEIGHT BY CLASSES OF WAREHOUSES

Hundredweights (000's omitted)	Line		Co-operative		Independent		All	
	No.	Average	No.	Average	No.	Average	No.	Average
		Cents		Cents		Cents		Cents
Up to 10	14	2.40	5	2.70	2	2.04	21	2.44
10 to 15	10	2.26	5	2.28	2	2.93	17	2.36
15 to 20	6	1.09	4	2.08	0	0.00	10	1.50
20 to 40	3	1.05	6	2.20	4	0.93	13	1.54
40 and over	0	0.00	6	1.13	4	1.32	10	1.18
All	33	1.77	26	1.65	12	1.34	71	1.60

Table XXIV shows that, taking the 71 warehouses, costs per hundredweight decrease quite consistently with volume of business. Curve A in Figure 9 shows the same thing graphically and in more detail. The costs for the ten largest volumes are appreciably smaller than for the next lower volume group of 13, but they are handling over 30,000 hundredweight more potatoes. The curve shows only slight decrease over 30,000 hundredweight, and especially over 50,000 hundredweight, and a very rapid decrease under 20,000 hundredweight. This indicates that there is a minimum of equipment which every warehouse must have, and costs decrease rapidly until this minimum is fully utilized; that from this point on to 30,000 hundredweight, the equipment is both increased and more fully utilized; and that above this point, equipment increases about as fast as volume of business, probably because certain major items have to be duplicated. Curve A may serve as a rough standard for purposes of comparison. If any warehouse finds its equipment costs are seriously out of line with this curve, it should determine the reasons for it and whether or not they are adequate.

Thus, as we examine individual warehouses, we find that No. 58, a line house, handling 11,000 hundredweight, has an equipment cost of 5.3 cents per hundredweight, nearly three times the average for this volume. Its building and other costs are somewhat high, but nothing in comparison with equipment costs. The volume of business is too small for a 36x70 ft. warehouse, but even if the volume of business were normal, equipment costs would be high. The equipment of the warehouse cost $2700 new, and the warehouse, $4450, a ratio of 60.8, as compared with 17.5 for the average. (See Table XXII.) This warehouse has a conveyor which cost $1500, and all other equipment in proportion.

Near the other extreme is No. 10, a co-operative house which handled 13,580 hundredweight at an equipment cost of 1.06 cents per hundredweight, about 0.7 cent under the average for this volume. The value of the equipment was only 8 per cent of the value of the building. The warehouse has no conveyors or elevators or dumping equipment. No doubt the warehouse could well afford to provide more convenient equipment.

No. 26, a co-operative warehouse, handled 230 cars at an equipment cost of 1.15 cents per hundredweight, which is perhaps a little high for this volume. The equipment cost 35 per cent as much as the warehouse, and is very complete.

No. 20, also a co-operative house, had as much equipment as No. 26 and handled only 32,000 hundredweight.

The lowest cost of all was for an independent house which handled 105 cars with $200 worth of old equipment. Needless to say, its labor costs were high. The highest cost for independents, 4.6 cents per hundredweight, was for a warehouse with $2800 worth of equipment handling only 40 cars. In this case, building costs were equally high.

Table XXV shows the distribution of equipment cost to five processes. Grading uses more equipment, on the average, than any other process. If all warehouses were equipped with conveyors and elevators and wagon dump scales, however, these percentages would be greatly changed.

TABLE XXV

DISTRIBUTION OF EQUIPMENT COSTS TO PROCESS

Process	Line		Co-operative		Independent		All warehouses	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Receiving	$ 26	12.4	$ 98	22.3	$135	32.7	$ 71	21.6
Grading	99	47.6	212	48.0	159	38.7	151	46.0
Sacking	5	2.4	14	3.1	12	2.8	9	2.8
Warehousing	39	18.6	67	15.2	54	13.0	52	15.7
Loading cars	40	19.0	50	11.4	53	12.8	46	13.9
Average	$209	100.0	$441	100.0	$412	100.0	$328	100.0

LABOR COST

Table I shows that labor is 24.7 per cent of all costs. Table XXVI shows the elements in labor cost. For the 71 warehouses the labor hired is 75.8 per cent of the total, and the labor performed by the manager is 23.6 per cent of the total. The division of the time of the manager between labor and office and management was a rough estimate. In general, time spent in buying and selling, correspondence, and keeping records was called office and management, and that devoted to the actual physical handling of the potatoes and the like was called labor. For the co-operative warehouses, labor was estimated as 45 per cent of the manager's time; for the independent houses, 27 per cent; and for the line houses, 53 per cent. As will appear later, a large part of the work of office and management for the line houses was performed in the central office. The local managers of such houses, therefore, had more time to devote to the actual labor of handling potatoes. Their smaller volume of business had the same effect.

TABLE XXVI

ELEMENTS OF LABOR COSTS FOR 71 WAREHOUSES

Elements of cost	Line		Co-operative		Independent		All warehouses	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Hired labor	$386	55.4	$1214	80.3	$1719	88.6	$913	75.8
Labor by manager	310	44.6	284	18.8	208	10.7	284	23.6
Liability insurance	*	*	14	.9	14	.7	7	.6
All	$696	100.0	$1512	100.0	$1940	100.0	$1205	100.0

* Employment liability included in home office overhead and prorated to office and management costs for each warehouse.

Twenty-seven of the 38 co-operative and independent warehouses carried liability insurance for employees amounting to $19.12 per warehouse, and about three fourths of this was charged to labor, the rest to office management. The line houses all carried liability insurance, but it has been included with office and management cost.

Labor costs may vary, either because the rates of pay are different or because of difference in the amount of labor used per hundredweight of potatoes handled. No analysis of labor costs which does not separate these two factors can be at all complete. The data needed for this are rates of pay by the day or hour, and days or hours worked. Such data were not obtained in the survey; in fact, can be obtained only as rough estimates by the survey method. In the analysis which follows, therefore, we shall consider directly variations in labor cost per hundredweight without taking up variations in rates of pay and hours per hundredweight.

If we could assume that rates of pay were the same for all warehouses, then labor cost per hundredweight would vary only because of differences in hours per hundredweight. The analysis which follows will roughly assume this. It will misrepresent the facts to the extent that rates of pay for hired labor vary in different warehouses, and to the extent that managers' salaries are different for various warehouses, and to the extent that each warehouse uses a different proportion of the manager's time at ordinary labor. A careful analysis of rates would, of course, show perhaps three different rates for the manager's time, a high rate for time spent in buying and selling, a somewhat lower rate for time spent on the records, and a still lower one for time spent at labor. But even this latter rate would be higher than the rates paid for hired labor.

LABOR COSTS PER HUNDREDWEIGHT

Table XXVII shows that the range in labor costs is from less than 4 cents to more than 11 cents per hundredweight. For all classes combined, over 50 per cent have labor costs between 5 and 7 cents per hundredweight, 18 per cent are under 5 cents, and 27 per cent are above 5 cents. Relatively more of the line and independent warehouses have costs over 7 cents per hundredweight, and relatively more of the co-operatives have costs under 5 cents per hundredweight. But the two highest labor costs are for co-operative warehouses. These high costs are very serious and must be reduced in most cases if the warehouse is going to succeed. Let us analyze the data to see the reason for the high costs and also for the low costs. It will not be possible, however, to single out all the reasons for the variations in labor costs. In the first place, not all the data needed are available; for example, as already explained, no data are available as to hours of labor and rates per hour; and there are many irregularities in the data obtained.

TABLE XXVII

Range in Labor Costs per Hundredweight, by Classes of Warehouses

Labor costs per hundredweight	No. in group			
	Line	Co-operative	Independent	All
Cents				
Less than 4	3	1	1	5
4 to 5	1	6	1	8
5 to 6	10	5	3	18
6 to 7	9	9	3	21
7 to 8	7	1	2	10
8 to 9	3	1	0	4
9 to 10	0	1	2	3
10 to 11	0	1	0	1
11 to 12	0	1	0	1
All	33	26	12	71

Table XXVIII shows that difference in volume of business is one reason for difference in labor costs per hundredweight, but by no means the most important reason, as the labor cost for the 21 warehouses handling less than 10,000 hundredweight averaged only 2 cents more than for the group of 10 handling over 40,000 hundredweight, whereas the range in costs with any one volume group is anywhere from 4.2 to 6.2 cents. Table XXIX shows that for the 12 independent houses there is scarcely any decrease in cost with volume of business. By the same sign, volume is a somewhat more important factor in determining labor costs when line and co-operative warehouses are considered separately; but still not the main factor.

TABLE XXVIII

Relation of Volume of Business to Labor Costs per Hundredweight in 71 Warehouses

Hundredweights (000's omitted)	No. in group	Labor cost per warehouse	Labor cost per cwt.		
			High	Low	Average
			Cents	Cents	Cents
Under 10	21	$ 534	11.43	5.21	7.40
10 to 15	17	714	9.56	4.61	5.95
15 to 20	10	1059	7.29	3.02	6.03
20 to 40	13	1551	9.58	3.56	5.85
40 and over	10	3137	9.42	3.75	5.44
All	71	$1205	11.43	3.02	5.89

TABLE XXIX

Labor Cost per Hundredweight by Classes of Warehouses

Hundredweights (000's omitted)	Line		Co-operative		Independent	
	No. in group	Av. for group	No. in group	Av. for group	No. in group	Av. for group
		Cents		Cents		Cents
Up to 10	14	7.22	5	8.19	2	6.52
10 to 15	10	6.06	5	5.78	2	5.88
15 to 20	6	5.67	4	6.52	..	...
20 to 40	3	3.98	6	6.01	4	6.74
40 and over	..	...	6	5.04	4	6.14
All	33	5.88	26	5.65	12	6.33

One of the principal reasons for the irregularities in labor costs is the attempt to divide the manager's time between labor and office management. Yet this separation was necessary in order to reduce labor costs of line houses and other warehouses to a comparable basis, as such a large part of office and management work for line houses is done in the central office. If the three types of warehouses are considered separately, however, the payroll can be considered as a unit. This method of analysis will, therefore, be followed for a while.

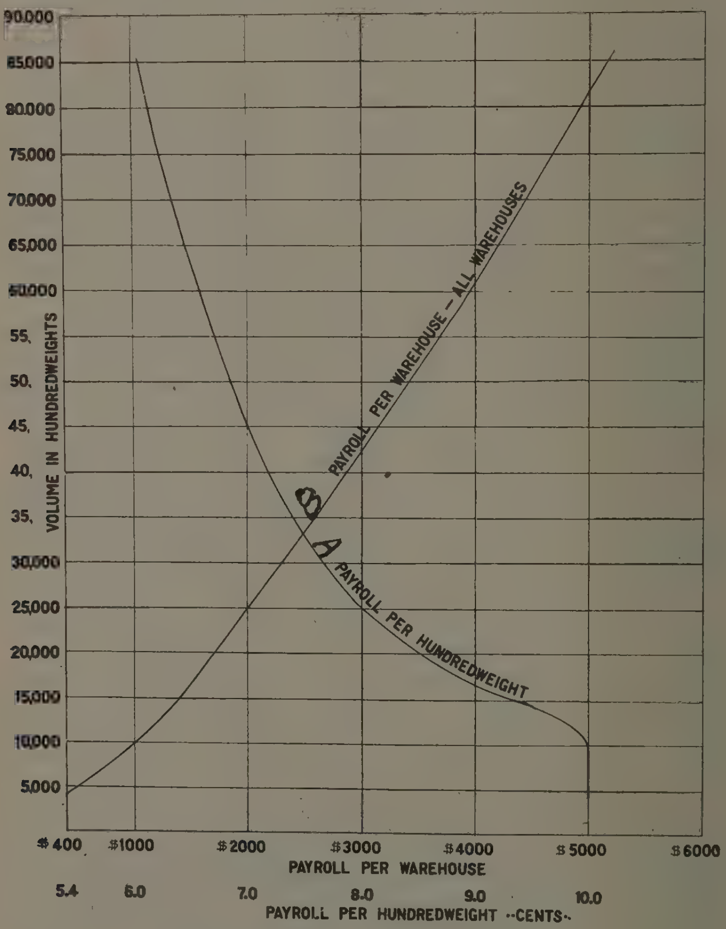

Fig. 10. Payroll per Warehouse, Increasing with Volume of Business; and Payroll per Hundredweight, Decreasing with Volume

Figure 10 shows graphically the relation between payroll and volume of business for all warehouses. Curve B is drawn freehand approximately through the midpoints of the groups arranged on the basis of volume. It therefore expresses in rough average form the way in which payroll increases with output. Curve A shows the same relationship expressed in the form of payroll per hundredweight. If any warehouse has a payroll or payroll per hundredweight seriously out of line with the curve in Figure 10, there should be a reason for it, a sound reason which can be justified before the board of directors.

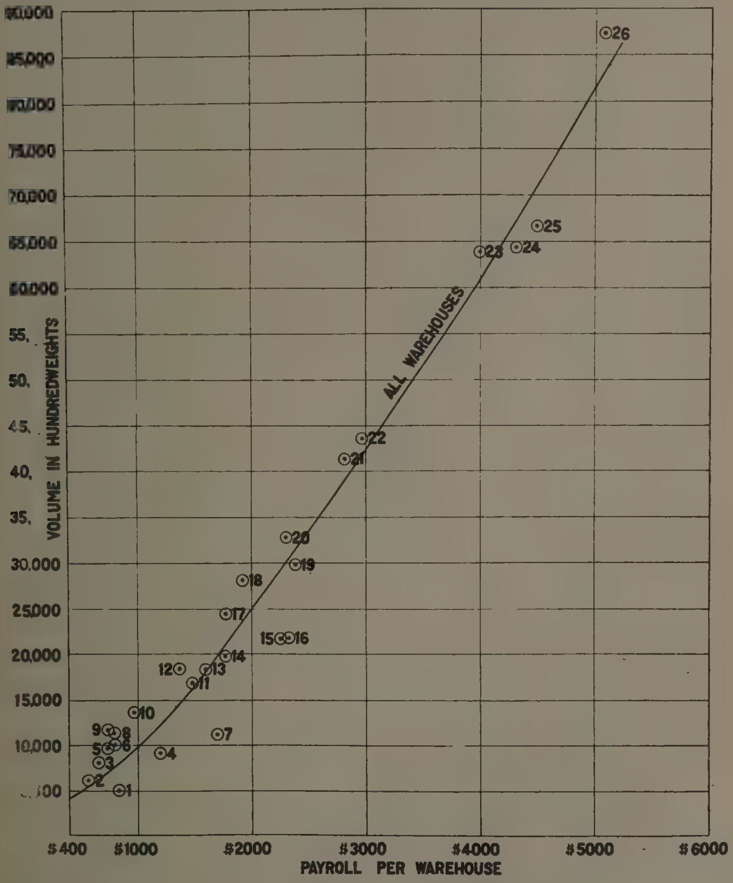

Fig. 11. Payrolls of Individual Co-operative Warehouses Compared with Average for All Warehouses of the Same Volume
(The curve represents the average for all warehouses.)

CO-OPERATIVE WAREHOUSES

Let us examine some of the warehouses that are seriously out of line, co-operative warehouses first. Table XXX shows the increase in payroll with volume of business and the effect of this on payroll per hundredweight. The range in payroll costs per hundredweight is from

6.5 cents for those handling over 40,000 hundredweight to 11.5 cents for those handling under 10,000 hundredweight. This is a range of 64 per cent of the average, which is to be compared with 56 per cent of the average for labor costs considered separately. (See Table XXIX.) The range within volume groups is correspondingly a little narrower, especially for the larger volumes. Figure 11 reproduces Curve B from Figure 10 and locates against the curve the 25 co-operative warehouses. It will be apparent that in general the payrolls of co-operative warehouses do not vary greatly from the average. The small co-operative warehouses, however, those with volume under 12,000 hundredweight, have lower payrolls than the average. Table XXX shows that this is because they pay their managers very low salaries. Table XXXI shows that the line houses in the volume group under 10,000 hundredweight paid their managers an average of $527, or $155 more than the co-operatives, and in the volume group from 10,000 to 15,000 hundredweight, $715, or $111 more than the co-operatives. The line houses probably realize better than the co-operatives the importance of a skillful manager even for a small business. The small line houses also stored a few more potatoes than the small co-operatives.

TABLE XXX

RELATION OF PAYROLL TO VOLUME OF BUSINESS OF CO-OPERATIVE WAREHOUSES

Hundredweights (000's omitted)	No. in group	Per warehouse			Per hundredweight		
		Managers' salaries	Other payroll	Total	High	Low	Average
					Cents	Cents	Cents
Under 10	5	$372	$506	$878	19.4	8.5	11.5
10 to 15	5	604	447	1051	15.7	6.5	9.1
15 to 20	4	911	902	1813	13.1	8.7	9.8
20 to 40	6	891	1337	2228	11.4	6.8	8.4
Over 40	6	1068	2881	3949	6.9	6.3	6.5
All	26	$780	$1295	$2075	19.4	6.3	7.8

TABLE XXXI

RELATION OF PAYROLL TO VOLUME OF BUSINESS OF 33 LINE HOUSES

Hundredweights (000's omitted)	No. in group	Per warehouse			Per hundredweight		
		Managers' salaries	Other payroll	Total	High	Low	Average
					Cents	Cents	Cents
Under 10	14	$527	$117	$644	13.6	7.8	10.1
10 to 15	10	715	495	1210	12.1	6.9	10.3
15 to 20	6	1025	589	1614	11.0	6.8	9.5
20 to 40	3	1110	484	1694	7.3	6.7	6.9
Over 40	..	....	....	....	...	..	..
All	33	$729	$688	$1417	13.6	6.7	9.4

The co-operative warehouses whose payroll is a little high are Nos. 1, 4, 7, 15, and 16. For No. 1, this is solely because the manager's salary is a little high for the volume of business handled. The apparent reason for this is that less business was handled than was expected. Miscalculation of this is unavoidable. In No. 4, considerable storing was done, and the manager was hired for a longer period than ordinarily. For No. 7 it seems to be due to high labor costs, apparently partly to inadequate equipment. For No. 15 it is due to very high manager's salary, and for No. 16 to very high labor costs. However, the plant seems to be well equipped, hence we must conclude that more labor was hired than needed, or that high wages were paid, or that the potatoes were very carefully sorted and graded, which may or may not have justified the extra cost.

LINE HOUSES

Figure 12 shows the location of payroll of the 33 line houses as compared with the average for the same volume. It will be noted that the payroll is higher than the average for the smaller volumes of business, and somewhat smaller than the average for volumes of business between 15,000 and 20,000 hundredweight. Table XXXI gives the data for this. Apparently the salary of the manager is responsible for most of the higher payrolls. In every volume group, but especially in the smaller ones, managers' salaries are higher than for co-operative warehouses. On the other hand, other payroll costs are lower—for the 14 co-operative warehouses handling less than 20,000 hundredweight, they average $598; for the 30 line houses of the same volume group, $371. As already pointed out, the managers of the line houses themselves do more of the work of handling the potatoes. Apparently 10 000 hundredweight or less can be handled by a manager of a line house with little or no extra labor; and above 10,000 hundredweight, about as much extra labor is needed for 12,000 as for 20,000 hundredweight. Utilization of labor is, therefore, partly a matter of adjustment of labor to volume of business. The co-operatives are apparently more likely to over-estimate volume of business than the line houses.

The line house payrolls most out of line are Nos. 58, 66, 67, 68, and 69. No. 58 operated on a combined commission and salary basis and had a low cost for other labor. Apparently the manager worked hard. The salaries of Nos. 68 and 69 were both low for the amount of business handled. The line houses show a slight tendency not to proportion salaries to larger volumes of business. No. 66, however, is a case to the contrary. The payroll of No. 67 is due to high extra labor costs. This warehouse handled 18,000 hundredweight practically without equipment.

The range in payroll cost per hundredweight for line warehouses is less than for co-operatives because the range in volume is less. For the same range in volume, it is greater if the group of three largest volumes is included, but otherwise less. The range between high and low costs is also less for the line houses. This is in keeping with the common observation that line companies tend to standardize their costs more than do independents and co-operatives.

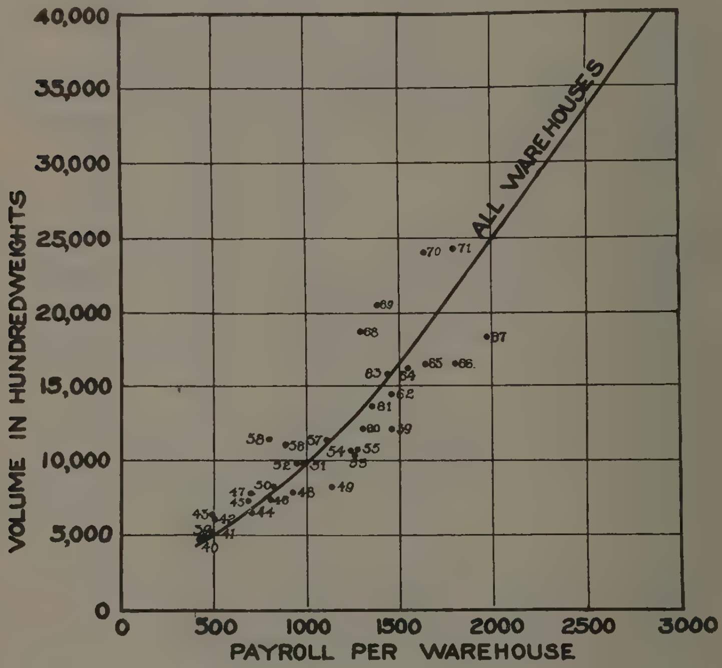

Fig. 12. Payroll of Line Houses Compared with Payrolls of All Warehouses of the Same Volume

The average payroll costs per hundredweight are 1.6 cents higher for line than for co-operative houses. For those under 20,000 hundredweight, however, the line house payroll costs are 9.7 cents per hundredweight, and the co-operatives' 10.2 cents per hundredweight. If the group 20,000 to 40,000 is included, the line houses will appear still more to advantage.

It should be pointed out here, however, that the manager of a co-operative house has more responsibility than the manager of a line house, and handles a larger proportion of the actual selling of the potatoes.

INDEPENDENT WAREHOUSES

There are not enough independent warehouses to give a good distribution, but it is obvious from Figure 13 that any sample taken would show more variations than for the other classes. The principal reason for this is that the operators of independent warehouses were erratic in estimating salaries for themselves. Apparently they did not standardize their salaries high on the whole. Nos. 27, 28, 33, 35, and 38 were especially low in their estimates.

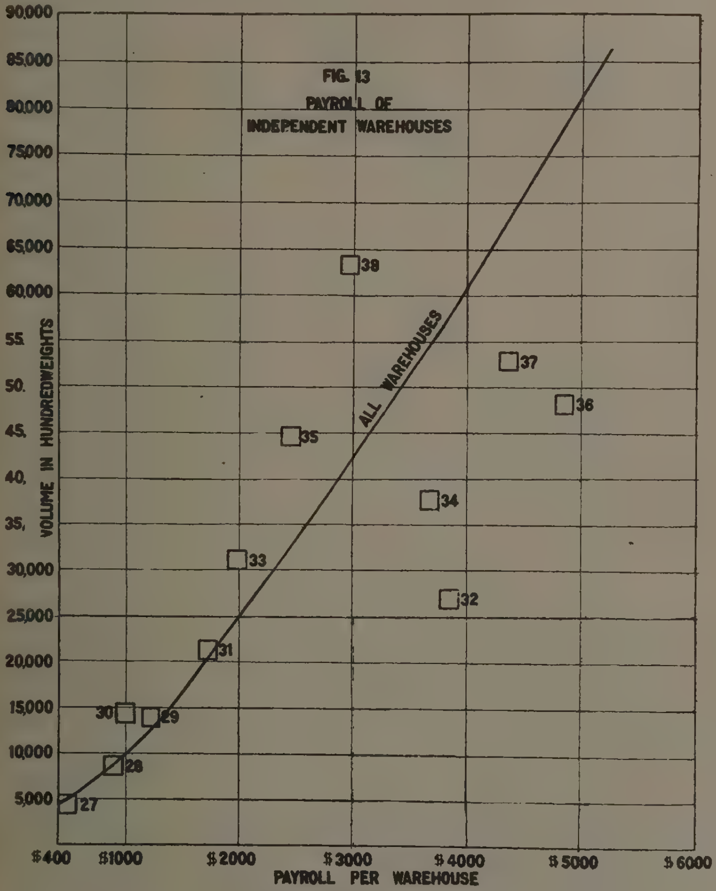

Fig. 13. Payrolls of Independent Warehouses Compared with Payrolls of All Warehouses with the Same Volume

Table XXXII shows that other payroll costs average $452 for the 4 handling less than 15,000 hundredweight, as compared with $476 for 10 co-operative and $274 for 24 line houses of the same volume groups.

The four large independent houses handled an average of 52,357 hundredweight (see Table X) with payrolls averaging $3220; the 6 large co-operatives handled an average of 61167 hundredweight with a payroll cost of $2881. The comparison for the 20,000 to 40,000 hundredweight group is about equally favorable to the co-operatives. Hence, in spite of a considerably larger average volume of business the independents show higher total payroll costs per hundredweight than the co-operatives. The 4 small independent houses show low costs, but the operators estimated their salaries at an average of only $312.

TABLE XXXII

RELATION OF PAYROLL TO VOLUME OF BUSINESS, INDEPENDENT WAREHOUSES

Hundredweights (000's omitted)	No. in group	Per warehouse			Per hundredweight		
		Managers' salaries	Other payroll	Total	High	Low	Average
					Cents	Cents	Cents
Under 10	2	$220	$361	$581	9.6	8.4	8.8
10 to 15	2	605	542	1,147	9.0	7.2	8.1
15 to 20	..	....	....	....	....	..	..
20 to 40	4	1060	1800	2,860	14.5	6.5	9.8
Over 40	4	825	3220	11,445	10.2	4.9	7.7
All	12	$766	$1657	$2,423	14.5	4.9	8.5

The costs for No. 32 are high because of a high estimated salary, and of Nos. 37 and 38 because of high payroll costs. To illustrate the difference in this respect, No. 38 handled 176 cars with payroll costs of $1882; No. 34, 105 cars at $2397; No. 37, 142 cars at $3416; and No. 36, 134 cars at $4392. This is a range from 3.3 cents to 9.4 cents a hundredweight.

TWO DIMENSIONS OF PAYROLL

It will be apparent from the foregoing discussion that a payroll may be high for a given volume either because too much labor is employed or because wages and salaries are high. It is not possible, with the data obtained in the survey, to show which of these is the more important cause in each case. In general, however, variations in amounts of labor used is the more important of the two causes. This means that warehouse managers need to look to the amount of labor employed as a source of high labor costs in many cases. Better and more complete equipment would help in many cases; in others, a better estimate in advance as to the amount of business to be handled.

DISTRIBUTION OF LABOR COSTS

Labor was distributed to the five processes on the basis of the manager's estimates of the actual division of time of the different employees between different operations. The data in Table XXXIII therefore indicate the distribution only in a general way. Warehousing and sacking seem to be the most time-consuming operations, and constitute nearly two thirds of the total. The operations of receiving the potatoes and loading them into cars represent less than one fifth of the total. Different warehouses vary greatly in the proportion of labor used for different operations, depending upon equipment, arrangement of warehouse, amount of storing, and the like.

TABLE XXXIII

Distribution of Labor to Processes

Operation	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Receiving	$ 38	5.4	$124	8.2	$120	6.2	$ 83	6.9
Grading	126	18.1	301	19.9	340	17.5	227	18.8
Sacking	186	26.7	410	27.1	545	28.1	329	27.3
Warehousing	271	39.0	496	32.8	702	36.2	427	35.4
Loading cars	75	10.8	181	12.0	233	12.0	140	11.6
Total av.	$696	100.0	$1512	100.0	$1940	100.0	$1205	100.0

OFFICE AND MANAGEMENT COST

Table I shows that office and management cost represents 26.7 per cent of all costs. It is thus a more important cost classification than labor. Of the $1554 charged to office and management for line houses, $996, or 64 per cent, represents central office costs distributed to the local line houses. The records of the central office charged the more direct expenses to particular local warehouses, but did not distribute salaries and similar items. These were prorated between locals arbitrarily on the basis of hundredweights of potatoes handled. This was not an entirely satisfactory basis of allocation, as some of the services performed in the central office did not vary with volume and, therefore, might better be allocated on a per warehouse basis. The correct procedure in such a case is to classify the time of the central office employees according to the basis on which it should be allocated, and to handle each classification in its proper way; but this ordinarily requires more detail than is possible with survey methods. The effect of using this method was, of course, to reduce the range of variations in office and management for line houses, especially the variations with volume.

None of the data for office and management cost, however, are very accurate. One reason for this is the one already pointed out, namely, that the payroll had to be divided more or less arbitrarily between labor, and office and management.

Table XXXIV shows the elements in office and management cost. Management cost includes the cost of that part of the time of the manager which is devoted to buying and selling and directing the work of the other employees. Office cost includes the cost of that part of the time of the manager which is devoted to records and correspondence; also the salaries of the office helpers of all kinds, and such expenses as stationery and office supplies, telephone and telegraph, and the like. Table XXXV shows the division of office and management costs of line houses between the central office and the local units. The largest item of expense is salaries of managers, officers, and office employees, amounting to 59 per cent of the total. For the line houses, the salaries assigned to the central office, $454, represent 29 per cent of the total; the salaries of the local management, $409, represent 26.3 per cent; and the salaries of the office help, $128, all in the central office, represent 8.2 per cent. The total of these is $863, or 55.5 per cent.

TABLE XXXIV

ELEMENTS IN OFFICE AND MANAGEMENT COSTS BY CLASSES OF WAREHOUSES

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Officers' salaries	$ 60	3.9	$ 47	4.9	$ 84	6.3	$ 59	4.5
Managers' salaries	675	43.4	492	50.9	587	44.0	593	45.6
Office salaries	128	8.2	67	6.9	65	4.9	95	7.3
Office supplies	28	1.8	48	5.0	56	4.2	40	3.1
Telephone and telegraph	133	8.6	61	6.3	201	15.1	118	9.1
Market service	40	2.6	12	1.2	15	1.1	25	1.9
Interest	118	7.6	138	14.3	191	14.3	138	10.0
Miscellaneous	372	23.9	101	10.5	135	10.1	233	17.9
Total	$1554	100.0	$966	100.0	$1333	100.0	$1301	100.0

TABLE XXXV

DIVISION OF OFFICE AND MANAGEMENT COSTS PER WAREHOUSE BETWEEN CENTRAL OFFICE AND LOCAL WAREHOUSE FOR 33 LINE HOUSES

	Central office		Local warehouse	
	Amount	Per cent of total	Amount	Per cent of total
Officers' salaries	$ 60	5.4		
Managers' salaries	266	23.9	$409	93.0
Office salaries	128	11.5		
Office supplies	28	2.5		
Telephone and telegraph	122	10.9	11	2.5
Market service	40	3.6		
Interest	118	10.6		
Miscellaneous	352	31.6	20	4.5
Total	$1114	100.0	$440	100.0

The next largest item is interest. This represents interest actually paid on funds required to carry on the current business of the warehouse, plus interest at a similar rate on any funds belonging to the business and used in the same way. It is interest on what may be called the "quick assets" of the business. These funds are tied up during the operating season in potatoes, sacks, labor, and other current inventories. For the co-operative houses, most of this quick capital was borrowed; for the line houses, more of it was owned than borrowed.

Office salaries represent salaries of bookkeepers or secretaries paid by 7 co-operative warehouses and by one independent warehouse, averaging $314 per warehouse for the 8. If one very high salary is omitted, the average for the other 7 is only $240. For all other co-operatives and independents the records and accounts were kept by the managers. The effect of employing special help for this in the case of the 8 warehouses was simply to release more of the manager's time for labor at handling potatoes.

A comparison of office and management expenses for the three classes of warehouses shows that they are much higher for line houses than for co-operatives and independents. The items mostly responsible for this are managers' salaries, office salaries, and miscellaneous. The salaries of the local managers of line houses are lower than those of the managers of co-operatives, but to these local salaries must be added $266 as the prorated share in the salaries of management in the central office. Office salaries in the local warehouses are the salaries of those who handle the records and accounts and correspondence in so far as it is not done by the managers themselves. In a line-house organization, as much as possible of this record keeping and correspondence is handled in the central office. The cost of record keeping and management is higher for the line houses for two reasons, one is that better records are kept, and the other that the central office of a line-house organization is a selling organization. As already explained, the co-operative houses sell only a small part of their potatoes themselves, whereas a line-house organization sells nearly all. It has not been possible in the survey to determine the central market selling expenses of individual co-operative and independent houses, but later in the bulletin, some rough averages will be given as to the amount of such costs which will make possible a general comparison with line-house selling expenses. At this point in the analysis, the reader must keep in mind that the office and management costs of the line-house organizations represent much more service than the office and management costs of most co-operative and independent warehouses.

This also accounts for the much higher miscellaneous costs of the line houses. Included in the miscellaneous costs of the central office are such items as automobile costs, traveling expenses, advertising and publicity, insurance, postage, exchange, depreciation on furniture and fixtures, office rent, and wages of yard men. A local co-operative or independent warehouse incurs some of this expense, but usually the items are small, especially if the local is doing little of its own selling, as is usually the case. It will be noted that the miscellaneous expense of local line houses is only $20 as compared with $101 and $135 respectively for co-operative and independent warehouses. This indicates that the central office of a line-house organization takes over most of the functions which cause co-operative and independent warehouses to incur the various miscellaneous expenses.

The central office, it appears, takes over the whole burden of furnishing the quick capital of the business. Telephone and telegraph and market service costs of the line-house organizations are also appreciably higher than for the other classes of warehouses, which is what one would expect in view of the extra selling service performed.

It is rather significant that altho the absolute office and management payrolls per warehouse of line-house organizations are somewhat larger than for the other classes of warehouses—$863, as compared with $606 for co-operatives, and $736 for independents—the ratio of payroll costs to total office and management costs is relatively low (55.5 per cent) as compared with 62.5 per cent for co-operatives, and 55.2 per cent for independents. When these various costs are reduced to a hundredweight basis, however, the comparison takes on a quite different aspect.

OFFICE AND MANAGEMENT COST PER HUNDREDWEIGHT

Table XXXVII shows that the average office and management cost per hundredweight for the 71 warehouses was 6.4 cents, and that the range was from 1.3 to 17.9 cents. Table XXXVI shows that the office and management costs for co-operative and independent warehouses were nearly all under 8 cents per hundredweight, and for the line houses, all were over 8 cents per hundredweight. Table XXXVIII shows that the average for co-operatives was 3.6 cents; for independents, 4.3 cents, and for line houses, 13.1 cents. The smaller volume of business handled by the line houses makes this cost very high when reduced to a hundredweight basis. As already explained, this is in large measure due to the fact that the line-house organizations do their own selling, whereas the others hire it done. That this is not the whole explanation is indicated by the fact that the office and management payrolls of the local line houses alone were 3.5 cents per hundredweight, as compared with 2.6 cents for co-operative, and 2.1 cents for independent houses.

TABLE XXXVI

RANGE IN OFFICE AND MANAGEMENT COST, BY CLASSES OF WAREHOUSES

Cost per cwt.	No. in group			
	Line	Co-operative	Independent	All
Cents				
Under 2	0	3	2	5
2 to 4	0	8	3	11
4 to 6	0	10	2	12
6 to 8	0	4	3	7
8 to 10	4	1	2	7
10 to 12	7	0	0	7
12 to 14	11	0	0	11
14 to 16	7	0	0	7
16 to 18	4	0	0	4
All	33	26	12	71

TABLE XXXVII

RELATION OF VOLUME OF BUSINESS TO OFFICE AND MANAGEMENT COSTS PER HUNDREDWEIGHT FOR 71 WAREHOUSES

Hundredweight (000's omitted)	No. in group	Per warehouse	Per hundredweight		
			High	Low	Average
			Cents	Cents	Cents
Under 10	21	$710	15.9	2.7	9.8
10 to 15	17	1277	17.9	3.3	10.7
15 to 20	10	1761	16.0	2.2	10.0
20 to 40	13	1591	12.7	1.9	6.0
40 and over	10	1739	5.2	1.3	3.0
All	71	1300	17.9	1.3	6.4

TABLE XXXVIII

OFFICE AND MANAGEMENT COST PER HUNDREDWEIGHT BY CLASSES OF WAREHOUSES

Hundredweights (000's omitted)	Line		Co-operative		Independent	
	No. in group	Average for group	No. in group	Average for group	No. in group	Average for group
		Cents		Cents		Cents
Under 10	14	12.3	5	5.2	2	4.9
10 to 15	10	14.5	5	5.0	2	6.1
15 to 20	6	13.5	4	5.3	..	..
20 to 40	3	11.6	6	3.8	4	5.7
40 and over	..	....	6	2.8	4	3.3
All	33	13.1	26	3.6	12	4.3

The correlation of office and management cost with volume of business in Table XXXVII is misleading in view of the fact that a majority of the small warehouses are line houses which did their own selling, and most of the large houses are co-operatives and independents which did little or no selling. This same correlation, however, is indicated in Table XXXVIII by classes of warehouses. For the co-operatives, the office and management costs of the largest 6 warehouses handling an average of 61,166 hundredweight were 54 per cent of the same costs of the smallest 5 handling an average of 7631 hundredweight. For the independents, the same costs for the 4 largest, handling an average of 52,357 hundredweight, were 67 per cent of the costs for the 2 smallest, handling an average of 6606 hundredweight. The analysis for the different warehouses of the line houses is of very little value, for the reason already given, that the central office costs, constituting 72 per cent of the total, were mostly prorated to the different warehouses as a flat rate per hundredweight. The small decrease in costs per hundredweight with volume that does appear, is mostly due to variation in local office and management costs, chief of which is the salary of the manager.

Figure 14 shows graphically the relation between volume of business and office and management costs per warehouse (Curve B) and per hundredweight (Curve A) for the co-operative and independent warehouses; and shows the location with respect to Curve B for each of the co-operative and independent warehouses. The distribution is rather irregular, and the number of cases is hardly adequate to furnish the basis for such a curve. A principle reason for the irregularities is, of course, the errors made in dividing payroll between labor and office and management. The diagram itself, however, furnishes a rough basis for testing the office and management cost of any local warehouse. Curve C represents a rough average by volume of the local costs of line warehouses. It is interesting to note that office and management costs increase more rapidly than volume of business for warehouses under around 10,000 hundredweight. Curve A in Figure 10, representing payroll, showed a slight tendency of the same sort. It now appears that this tendency was derived from the office and management part of the payroll. This is in keeping with general observation and experience with respect to management cost in small business units. The very smallest units in the fields of both merchandising and manufacturing, are managed with very little tangible outlay for management —what managing is needed can be carried on incidentally to the labor part of the business. A point in size is soon reached, however, at which considerable special time must be used for managing, and it is usually at a point not far beyond this that per unit management costs are highest. Above this point, unit management costs frequently decrease even more rapidly than unit labor costs. In this case, of course, the condition resulted because the managers of very small warehouses designated a very small part of their time as used especially in managing.

When individual records are examined in more detail, further reasons are noted for some of the wide variations that occur. No. 12, for example, employed a bookkeeper at a salary of $930, altho handling only 18,000 hundredweight of potatoes. No. 15 paid its manager $1500, altho handling only 21,000 hundredweight. A small sideline business was made the excuse for hiring a full-time manager. Did it pay? At the other extreme is No. 25, which handled 67,000 hundredweight with a $350 manager, and interest and all other costs low in proportion; and No. 21, which handled 41,000 hundredweight with a $300 manager, only $50 interest, no market service, and a negligible telegraph expense.

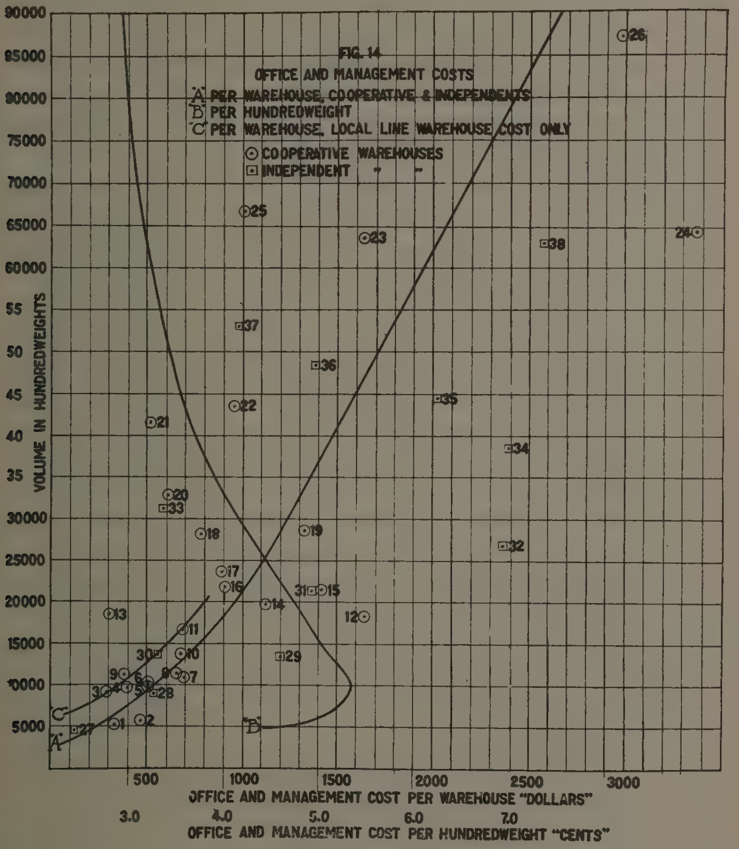

Fig. 14. Average Office and Management Costs of Warehouses, by Volume of Business

These are, of course, only costs—they do not indicate the amount and quality of the service that was rendered in return for the expenses incurred. For No. 26, for example, office and management costs were a little high. This warehouse sold practically all its crop direct to farm bureaus and dealers in the Corn Belt. No. 38, whose cost's are also high, sold all but one car direct to retailers. But No. 22 had low costs and yet sold its crop either on track, or direct to retailers. On the other hand, both No. 12 and No. 15, already mentioned, sold mostly through the Minnesota Potato Exchange. However, in spite of these irregularities, office and management costs show the effects of different methods of selling. After allowance was made for difference in volume of business, 16 of the 38 co-operative and independent warehouses, represented in Figure 13, which consigned all or most of their potatoes to commission firms, brokers, the Minnesota Potato Exchange, and the like, had average office and management costs 14 per cent under the average; 10 which sold mostly on track had average office and management costs 3 per cent above the average; and 6 which sold mostly direct to retailers, farm bureaus, and the like, had average office and management costs 33 per cent above the average. This means that for a co-operative or independent warehouse the office and management cost of selling an average volume of potatoes (20,449 hundredweight) direct would have been 5.3 cents per hundredweight; selling on track, 4.0 cents per hundredweight; and consigning, 3.3 cents per hundredweight. This represents a difference between the two extremes of 2 cents per hundredweight, or about $7 per car.

Differences in selling methods are one of the principal reasons for variations in several of the elements that make up office and management cost, especially telegraph and telephone, market service, manager's salary, and interest. Telegraph and telephone and market service cost the 38 independent and co-operative houses about 0.43 cent per hundredweight; and the 6 doing mostly direct selling, 0.53 cent per hundredweight, even tho they handled one half more business. Office and management salaries represent as high a rate per hundredweight for the 6 handling an average of 42,000 hundredweight, as for the 38 handling an average of 28,000 hundredweight; and the same is true of other office costs. The average interest cost on working capital was 0.56 cent for the 38, and 0.61 cent for the 6 doing direct selling. The warehouses handling a larger volume apparently secured a more rapid turnover for their working capital.

Interest costs, however, are more dependent upon buying methods than upon selling methods. For the line houses buying a small volume altogether for cash and doing a relatively large amount of storing, the average interest cost for working capital was 1.0 cent per hundredweight; for the independent houses, which bought a much larger volume mostly for cash, the average was 0.62 cent per hundredweight; for the 26 co-operatives handling a somewhat smaller volume and many of them pooling, 0.52 cent per hundredweight; and for 9 co-operative warehouses which pooled and sold mostly through the Minnesota Potato Exchange, only 0,15 cent per hundredweight.

There are, however, wide variations in interest and other costs due to other causes than buying and selling methods. One warehouse incurred interest costs of $850 on 161 cars, buying for cash and selling entirely on consignment; another, only $209 on 230 cars, buying for cash and selling direct. The former stored only 42 cars and the latter 52 cars. Interest is a cost that needs to be watched very closely. As already indicated, only 7 of the 38 warehouses paid special salaries for bookkeeping. Only 19 incurred any appreciable expenses for market and telegraph service, and the range in the amounts paid for such service was all the way from 50 cents a car (60 cars for $30), to $3 per car (15 cars for $45). One warehouse paid $435 for market and telephone service on 230 cars; another $210 for such service on 161 cars. Office supplies ranged from a few dollars to $159 for a warehouse handling only 51 cars. Included in miscellaneous costs are several items which varied greatly, for example, advertising and publicity, an expense incurred by only 11 of the 38, and ranging as high as $45 for a warehouse handling 28 cars.

An attempt was made to separate office and management cost between office and management. Office cost was defined to include everything except that portion of the manager's time which was devoted to buying and selling, supervision, and the like. Each manager was asked to estimate the division of his time between management and work on the records and accounts. Table XXXIX presents the results of this division. For all warehouses, the cost of management was 3.07 cents per hundredweight; of office, 3.13 per hundredweight, divided between 0.56 cent per hundredweight for time of the manager and 2.57 cents per hundredweight for other office costs. This calculation assumes the same rate for the manager at both types of work, which is not a proper assumption. The managers of co-operative houses spend relatively more of their time at office work than those of either line or independent warehouses. For both co-operatives and independents, the office is a larger cost than management. This is because it included, in addition to the items mentioned, the two large elements: interest, and market and telegraph service.

TABLE XXXIX

Division of Office and Management Cost Between Office and Management

Class	Manager's salary				Other office		Per hundredweight	
	Management		Office					
	Per warehouse	Per cwt.	Per warehouse	Per cwt.	Per warehouse	Per cwt.	All management	All office
		Cents		Cents		Cents	Cents	Cents
Line	$273	2.30	$135	1.14	$620	4.15	6.45	6.40
Co-operative	349	1.30	141	0.53	404	0.27	1.57	2.04
Independent	463	1.52	0	0.00	538	0.78	1.23	1.76
All	$333	1.62	$114	0.56	$526	2.57	3.07	3.13

Table XL attempts to show the distribution of office and management cost to processes. This table is to be interpreted more as indicating, in a general way, the authors' judgments as to how office and management cost is probably distributed than any definite results of statistical and accounting analyses. Some of the elements of office and management cost, it is true, could be definitely charged to buying, selling, and, in some cases, to warehousing; but for others this was not the case. In the latter class, especially were office and management salaries. The manager's office and management time was distributed first between buying, selling, and supervision, on the basis of his own estimates largely. Record keeping was considered as a part of buying and selling. The average distribution resulting was about as follows: buying, 25 per cent; selling, 35 per cent; supervision, 40 per cent. Next, supervision was distributed to receiving, grading, sacking, warehousing, and loading cars in proportion to the amount of labor used by each, it being assumed that supervision was more nearly proportional to labor than to space or equipment, or to all three combined. The assumption is, of course, not altogether sound—grading, for example, no doubt takes supervision out of proportion to labor—but it comes near enough to the truth for the purpose in hand. The errors resulting probably will not seriously affect the process-cost analysis, as office and management is so small a part of all of them except buying and selling, and makes up all of buying and selling.

TABLE XL

DISTRIBUTION OF OFFICE AND MANAGEMENT COSTS TO PROCESSES

Process	Line		Co-operative		Independent		All	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Buying	$544	35	$265	28	$403	30	$418	32
Receiving	11	1	19	2	16	1	14	1
Grading	34	2	58	6	48	4	46	4
Sacking	53	3	77	8	80	6	66	5
Warehousing	71	5	100	10	91	7	86	7
Loading cars	22	1	27	3	36	3	26	2
Selling	819	53	419	43	660	49	645	49
Total	$1554	100	$966	100	$1333	100	$1301	100

SALARIES OF MANAGERS

Table XLI shows the range in salaries of managers by classes of warehouses. Only five are over $1500, and all of these except one are for co-operative managers. The three highest salaries are $1700, $1800, and $2400. In three cases where considerable sidelines were handled, part of the salary was set aside for the sideline business. The salaries given are therefore for the potato business only.

In small warehouses, a large part of the manager's salary is merely wages of labor, and the same is true to some degree of the manager's salary in even the very large warehouses. The management is undoubtedly paid a higher rate than labor; and this should cause managers' salaries to tend to increase more rapidly than volume of business.

TABLE XLI

Range in Managers' Salaries by Classes of Warehouses

Annual salaries	No. in groups			
	Line	Co-operative	Independent	All
$ 100 to $ 300	3	3	1	7
300 to 600	7	6	4	17
600 to 900	14	5	4	23
900 to 1200	6	6	1	13
1200 to 1500	3	2	1	6
1500 and over	..	4	1	5
All	33	26	12	71

Table XLII shows that this effect is very evident with warehouses handling less than 15,000 hundredweight, and especially with those handling less than 10,000 hundredweight. Above this point, however, this effect is more than offset by the better utilization of management itself. This table can serve as a rough general guide to salaries for warehouses with various volumes. The salaries given are only averages of salaries actually paid. Probably all are a little high for the volume indicated because the potato crop was short the year of the survey. Salaries of line and co-operative house managers are about the same over 15,000 bushels. Under this point, line-house salaries are about 10 per cent under the average, and co-operative warehouse salaries about 10 per cent above the average. The reason for this is that the line-house managers do not have as many records to keep, and do not have as much responsibility.

TABLE XLII

Variation in Salaries of Managers with Volume of Business

Volume	Salaries		
	Line	Co-operative	Both
5,000	$ 325	$ 375	$ 350
10,000	650	750	700
15,000	900	950	925
20,000	1050	1050	1050
25,000	1125	1125	1125
30,000	1200	1200	1200
40,000	1350	1350	1350
50,000	1500	1500	1500
60,000	1650	1650	1650
70,000	1800	1800	1800

OTHER DIRECT COSTS

Other direct costs include a miscellaneous group of items not properly included under the four principal elementary costs, because they vary for different reasons, or because they are not proratable to processes on the same basis.

Table XLIII lists these items and shows their relative importance for the three classes of warehouses. By far the largest item is sacks, tags, and twine, which is 92.7 per cent of all other direct costs, and 26.8 per cent of all warehouse costs.

TABLE XLIII

ELEMENTS IN OTHER DIRECT COSTS

Items of cost	Line		Co-operative		Independent		All	
	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total	Amount	Per cent of total
Sacks, tags, and twine	$678	89.0	$1753	94.2	$2060	93.5	$1306	92.7
Fuel	40	5.2	63	3.4	87	3.7	56	4.0
Insurance on potatoes	13	1.7	19	1.0	6	0.3	14	1.0
Rent of scales	12	1.6	2	0.1	....	....	6	0.4
Car linings	7	0.9	20	1.1	44	2.0	18	1.3
Drayage on potatoes	3	0.4	....	....	10	0.5	3	0.2
Miscellaneous	9	1.2	3	0.2	....	....	5	0.4
Total	$762	100.0	$1860	100.0	$2204	100.0	$1408	100.0

The ordinary range in other direct costs is from 5.5 to 8.0 cents per hundredweight of potatoes handled. The extreme variations are probably due to errors in inventory and the like. The average for line houses is 6.4 cents per hundredweight; for co-operatives, 7.0 cents; for independent houses, 7.2 cents; and for all combined, 6.9 cents.

Sacks, tags, and twine costs should be proportional to volume, except for difference in purchase price due to buying at different times, or buying in larger quantities as practiced by some of the larger houses. The average for the larger houses was, however, not quite one cent per hundredweight less than for the smaller houses. The average for the line houses was 5.8 cents; for the co-operatives, 6.6 cents; for the independents, 6.7 cents; and for all combined, 6.4 cents.

The remainder of the other direct costs average only $102 per warehouse, being slightly higher for the line houses than the others, principally because of higher fuel and insurance costs.

Most of the cars are already lined when they reach the warehouses, the managers preferring to ship on this basis. Even when they are lined by the local warehouses, the linings may be returned and used again several times. The car linings cost given is for 37 warehouses which did more or less car lining on this basis, most of them only a little.

Drayage cost is for hauling potatoes by only three warehouses, and amounted to $70 per warehouse for these three.

Rent of scales is for seven warehouses which paid for having their potatoes weighed on public scales, or rented scales for the season. The average cost for the seven warehouses was 0.5 cent per hundredweight.

Insurance on potatoes was paid by twenty-five warehouses, mostly line houses doing considerable storing, and amounted to 0.5 cent per hundredweight of potatoes stored.

Miscellaneous costs consisted of an assortment of unusual items, chief of which were traveling expenses, collection of claims, miscellaneous freight and express.

These other direct costs were distributed as follows:

Sacks, tags, twine, and drayage were not distributed.

Fuel was distributed on the same basis as building and site.

Insurance on potatoes was charged to storage.

Rent of scales was charged to receiving.

Car linings was charged to loading car.

Drayage on potatoes and miscellaneous were combined and carried as a miscellaneous item in the final distribution to processes.

PROCESS COSTS

In this section of the bulletin, the elementary costs will be distributed so far as possible or feasible to the several processes named in Table I, in order to furnish a method for closer analysis of the reasons for variations. Equipment cost, for example, has to be studied by individual items of equipment before much can be done in the way of reducing it. The warehouse which gets the fullest use of its graders, dump scales, and conveyors will have the lowest equipment costs, prices of equipment being the same. The same is true of labor and building space.

The data obtained in the survey, however, were not sufficiently complete to make such a detailed analysis possible in most cases. Therefore only a few tables of data will be included, and the rest will be merely suggestive. The data given must be understood as indicating only very roughly the relative importance of the various cost elements in each process and the reasons for variations.

BUYING COSTS

The only cost element charged to buying is office and management. According to Table XL, buying represents 32 per cent of all office and management cost, as compared with 49 per cent for selling. The office part of office and management cost, as separated in Table XXXIX, was almost all distributed to buying and selling, and in addition about

60 per cent of the manager's time. One important exception was interest cost, which in the case of warehouses buying for cash and storing was charged largely to warehousing.

Buying costs, according to Table I, are 8.6 per cent of all warehouse costs for all warehouses combined, but only 4.7 per cent for co-operative houses, and 6.1 per cent for independent houses. Table XL indicates 35 per cent of all office and management cost of line houses charged to buying as compared with 28 per cent for co-operatives. On a hundredweight basis, buying costs are 4.6 cents for line houses; 1 cent for co-operatives; and 1.3 cents for independents. Buying costs for line houses are high because all office and management costs of line houses are high, and also because buying is supervised closely by the main office.

Buying costs of co-operative and independent warehouses range mostly between 0.5 cent and 2 cents per hundredweight, the variations depending upon the salary rate for office and management cost, and the proportion of this cost charged to buying. As the latter is based entirely on estimates, the results are not worth careful analysis. No doubt, however, some warehouses are giving proportionally much more time to buying than are others. It is a very important part of the business of operating a warehouse, no matter what the methods may be. whether buying for cash, pooling, or buying on commission for a dealer. It is here that the contact with the grower is largely obtained, and it is through the contacts obtained at this time that the manager secures the support of his patrons or members, and enlists their co-operation in such important measures as standardizing varieties, keeping varieties pure, treating seed for disease, better harvesting methods, and field sorting. Pricing and buying a load of potatoes from a grower should be a painstaking operation, calling for knowledge of grades and prices, and the exercise of much diplomacy and tact. Any really satisfactory pooling system which gives due consideration to differences in quality will require the same care and pains.

The potato warehouse which really serves its community satisfactorily, in the future must be one which engages actively in improvement programs. One of the important problems of the future is to determine how work of this kind is to be carried on, whether by a manager employed during the growing, as well as the harvesting and marketing, season, or by a special agent operating on a county or some other basis.

RECEIVING COSTS

Receiving costs are 5.2 per cent of the costs of co-operative warehouses; 4.4 per cent of the costs of independent warehouses; and 2.5 per cent of the costs of line warehouses. On a hundredweight basis, the comparison is as follows: co-operatives, 1.09 cents; independents, 0.94 cent; line houses, 0.77 cent. Table LXIV, giving the elements of receiving cost, shows that line houses have low receiving costs in general because they have little building space set aside for receiving. It was pointed out earlier in the bulletin that many line houses sacrifice the convenience of their patrons for the sake of keeping operating costs down, and it is in the receiving department that this is particularly in evidence. Even receiving labor is greatly reduced. This means that the growers do most of the work of unloading.

TABLE LXIV

Elements of Receiving Cost

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Building	$ 4	4.9	$ 46	16.0	$ 17	5.9	$ 22	11.1
Labor	38	41.6	124	42.8	120	41.8	83	42.4
Equipment	26	28.6	98	33.9	135	46.8	71	35.9
Office and management	11	11.9	19	6.6	16	5.5	14	7.3
Other direct costs*	12	13.0	2	0.7	....	....	6	3.3
Total	$ 91	100.0	$289	100.0	$288	100.0	$196	100.0

* Scales rented by 7 warehouses.

The receiving process begins when the potatoes arrive at the warehouse, and ends when the potatoes are ready to be elevated to the graders. The only equipment usually involved is the wagon scale, either with or without a dump, and the power equipment to operate the dump. As already explained, many warehouses have their potatoes weighed at public scales and 7 paid for this weighing. The receiving equipment, if housed at all, is housed in a lean-to, usually of light construction. Only about one fourth of the warehouses had any building cost charged to receiving, and most of these were co-operative warehouses.

The range in receiving costs in co-operative and line warehouses is mostly from 0.7 cent to 2 cents per hundredweight, only 9 falling under this group, and only 4 going above it. For line houses, the range is mostly from 0.3 cent to 1.2 cents per hundredweight. The reasons for these variations appear when individual warehouse receiving costs are examined.

First of all, equipment costs vary greatly. Of the 71 warehouses, only 31 had dumping equipment. The receiving equipment costs of these 31 were 0.55 cent per hundredweight, as compared with 0.20 cent per hundredweight for the remaining 40 warehouses. Building costs charged to receiving for the 31 warehouses were 0.14 cent per hundredweight, as compared with 0.10 cent per hundredweight for the others. Labor costs charged to receiving were practically the same for the two groups. Dumping equipment saves warehouse labor, but still more the labor of the growers, who usually unload their own potatoes if dumps are not provided. Receiving costs of the warehouses without dumps average 0.77 cent per hundredweight; of those having dumps, 1.13 cents per hundredweight. But those without dumps are smaller. When the effect of this difference in volume was allowed for, it cost on the average about 13 cents more per wagon load, or 78 cents more per carload, to provide dumping equipment. Against this 11 cents must be set the extra time of the grower and his team both while actually unloading and while waiting in line to unload. In the rush of the potato harvesting season, this can easily amount to much more than 13 cents.

The argument against using dumps is frequently advanced that it results in more bruised potatoes. Modern equipment, however, is little open to this objection.

One of the most important determinants as to whether or not to install dumping equipment is volume of business. Table XLV shows that receiving costs per hundredweight of warehouses with dumping equipment decrease rapidly for warehouses handling under 20,000 hundredweight, but very little from here upward, the reason being that beyond this point equipment and space are duplicated. For warehouses without dumping equipment, receiving costs per hundredweight actually increase at the beginning, probably because additional labor is not so well utilized. At 10,000 hundredweight, dumping equipment costs 0.85 cent more per hundredweight; at 20,000 hundredweight, 0.42 cent; at 30,000 hundredweight, 0.33 cent.

TABLE XLV

Relation of Receiving Costs per Hundredweight to Volume of Business

Volume	With dumps	Without dumps
Cwt.	Cents	Cents
5,000	2.25	0.60
10,000	1.60	0.75
20,000	1.22	0.80
30,000	1.13	0.80
40,000	1.12	...
50,000	1.11	...
60,000	1.10	...
70,000	1.10	...

Individual warehouses, however, vary greatly from the averages in Table XLV. No. 15, handling 21,600 hundredweight, had receiving costs of 0.0186 per cent, owing to high equipment inventory; No. 18 handled 30,000 hundredweight with less than half as high an investment in receiving equipment.

GRADING COSTS

Table I shows that grading represents 10.9 per cent of all costs. The grading process begins with the elevating of the potatoes to the grader, and ends when the potatoes leave the grader to enter the sacks, or a conveyor, or a hopper. The equipment involved is the grader, sometimes with a special picking table, and the gas engine or motor to operate it. Graders range considerably in capacity, and the larger warehouses may have two or three graders. The labor is that of picking over the potatoes and of looking after the graders, which need considerable attention, owing to clogging and the like. Sometimes during the rush season, as many as four or five men are employed at this work. But at slack seasons, only one man may be employed, the potatoes being fed to the grader more slowly, or culled less carefully. The space requirements include the space actually occupied by the graders, and the work space around them.

Table XLVI shows that labor and equipment make up three fourths of all grading costs. The decrease in grading costs with volume of business will therefore depend principally upon these two elements. The decrease in equipment costs with volume is very rapid up to 20,000 hundredweight, to the point where a small-sized grader is fully utilized, and rather slow from here upward, either because larger graders are used, or because equipment is duplicated. The labor curve for grading cost follows the same general direction as for labor in general in Figure 10 and Table XXVIII; that is, it decreases rapidly up to 15,000 hundredweight, and less rapidly from there upward. But the decrease is less rapid at the beginning than for equipment, and somewhat faster above the middle. The special curve for labor used in grading is bent somewhat less than the general labor curve, as the extra labor hired for culling potatoes can frequently be pretty well adjusted to the needs from week to week.

TABLE XLVI

Elements of Grading Cost

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Building	$ 79	23.3	$139	19.7	$120	18.0	$108	20.4
Labor	126	37.2	301	42.3	340	50.9	226	42.7
Equipment	99	29.4	212	29.8	159	23.9	151	28.4
Office and management	34	10.1	58	8.2	48	7.2	45	8.5
Total	$338	100.0	$710	100.0	$667	100.0	$530	100.0

There is a wide range in grading costs for individual warehouses of about the same volume. These are accounted for mostly on the score of more or less grading capacity than is needed, or varying amounts of labor or wage rates for labor. The misfits in grading capacity and volume were partly due to wrong forecasts of volume of business, and partly to carelessness in adjusting grading capacity to the volume expected. Part of these misfits can surely be prevented. The variations in labor costs are partly due to different degrees of care in sorting the potatoes, and partly to carelessness in hiring the right amount and kind of labor. It is of course possible to spend more upon careful sorting than is worth while; but probably this does not very often happen. The more carefully growers can be induced to sort in the field, the less the labor cost of sorting at the warehouse. It is always a question, however, as to where it is cheaper to do it.

Some typical cases of high and low grading costs are the following: Nos. 8, 9, and 10 each handled about 11,000 hundredweight, one with one grader, one with two, and one with three, with motor equipment in proportion. Labor and building costs were about the same, and yet the range in grading costs was from 0.27 cent to 0.54 cent per hundredweight. No. 35 handled 45,000 hundredweight with two graders and half the labor expense of No. 36, handling 48,000 with three graders. The largest warehouse covered in the survey handled 83,000 hundredweight with three graders and $650 labor cost, which is one third under the average.

The average grading cost per hundredweight is 0.26 cent. The average for line houses is only 0.29 cent, in spite of their small volume of business. This is because they seem to have better utilization of labor and equipment than the co-operative and independent warehouses. The costs of grading were especially high for the co-operative warehouses. The ordinary range in grading costs per hundredweight was from 0.15 to 0.45 cent.

SACKING COSTS

The sacking process begins when the empty sacks are placed on the sack-holder and ends when the sacks have been filled, weighed, and sewed, ready to be conveyed to temporary or permanent storage. The only equipment used is the sack-holder and platform scales, but considerable work space may be needed for the filled sacks while they are waiting to be carried away. Labor is, of course, the major item of cost. Sacking cost will therefore vary with volume handled much as total labor cost varies. Other variations are due to differences in wage rates and adjustment of labor employed to labor needs. The average for all warehouses is 0.244 cent per hundredweight, nearly the same as for grading cost.

TABLE XLVII

Elements of Sacking Cost

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Building	$ 65	21.1	$127	20.3	$118	15.6	$ 97	19.3
Labor	186	60.2	410	65.2	545	72.3	329	65.6
Equipment	5	1.6	14	2.2	12	1.5	9	1.9
Office and management	53	17.1	77	12.3	80	10.6	66	13.2
Total	$309	100.0	$628	100.0	$755	100.0	$501	100.0

WAREHOUSING COSTS

Table I shows that warehousing represents 21.5 per cent of all warehouse costs. Warehousing represents a miscellaneous group of activities, including conveying potatoes to storage, running conveyors, re-sorting, carrying out culls, clearing out bins, running the stove, and looking after the warehouse during the storage period. It becomes, in a sense, the residual claimant for all the labor not charged to other processes. The labor charged to it is therefore probably higher than it should be. Some of the labor so used, however, has few alternative uses at the time, and would be rated low under an accurate system of cost accounting. The labor charged to warehousing is 35 per cent of the total. The most important element in warehouse cost is of course building and site. The $468 of building cost charged to warehousing in Table XLVIII is 73 per cent of the total building and site cost. The principal item of equipment involved in warehousing is the conveyor. But only 16 warehouses had conveyors. The equipment charge for the others is for trucks, stoves, and the like.

TABLE XLVIII

Elements of Warehousing Cost

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Building	$317	44.5	$618	47.6	$557	39.5	$468	44.7
Labor	271	38.2	496	38.1	702	49.9	427	40.8
Equipment	39	5.4	67	5.2	54	3.8	52	4.9
Office and management	71	10.0	100	7.7	91	6.4	86	8.2
Other direct costs*	14	1.9	19	1.4	6	0.4	14	1.4
Total	$712	100.0	$1300	100.0	$1410	100.0	$1046	100.0

* Insurance on potatoes in storage.

As labor and building constitute 85 per cent of all warehousing costs, the curve of decrease with volume will represent a combination of these two curves. This means that it will be less bent than the curve for labor, and more bent than the curve for buildings.

The problem of whether or not to install a conveyor system is an important one. If No. 26, with 83,000 hundredweight of potatoes, had installed the conveyor system now in No. 30, with 14,400 hundredweight, the annual equipment cost of warehousing resulting would have been 0.31 cent per hundredweight, instead of the 1.82 cents when installed in No. 30. The highest warehouse equipment cost is for a warehouse with an elaborate conveyor system costing $1500 which handled only 21,600 hundredweight the year of the survey. The data observed are not sufficiently detailed and accurate for the purpose, but it should be possible to determine with what volume of business a conveyor system will save enough labor to warrant its installation.

Another major cause of variations in warehousing cost is amount of storing done and the period for which stored. Unfortunately the data obtained are not sufficiently accurate to warrant publishing any comparative cost figures. The clearest evidence appears in the case of warehouses built especially large in order to provide storage space.

CAR LOADING COSTS

Car loading represents 4.7 per cent of all warehouse costs. It is therefore of about equal importance with receiving. Table XLIX shows that labor is 60.9 per cent of car loading cost, and equipment 19.8 per cent. The process includes, in most cases, either elevating the sacks to the second floor or conveying them in a sack elevator directly to the cars. Of the 71 warehouses, 53 had sack elevators. If no sack elevator is provided, the sacks are trucked into the car from the warehouse. The line houses are as well equipped, on the whole, with car loading equipment as are the co-operative warehouses. The decrease of car loading costs with volume follows a curve bent somewhat more sharply than the labor curve. One sack elevator serves any ordinary sized potato warehouse; hence the equipment cost of car loading decreases very rapidly with volume. The other variations in car loading costs are due to difference in wage rates, utilization of labor, and the like. A minor cause of variations is the cost of car lining and labor of preparing the cars. The line houses line fewer cars than do the others.

TABLE XLIX

ELEMENTS OF CAR LOADING COSTS

	Line		Co-operative		Independent		All	
	Amount	Per cent	Amount	Per cent	Amount	Per cent	Amount	Per cent
Labor	$ 75	52.4	$181	64.8	$233	63.5	$140	60.9
Equipment	40	27.6	50	18.0	53	14.5	46	19.8
Office and management	22	15.2	27	9.7	36	9.9	26	11.3
Other direct costs*	7	4.8	21	7.5	44	12.1	18	8.0
Total	$144	100.0	$280	100.0	$365	100.0	$230	100.0

* Car linings.

SELLING COSTS

Selling costs, consisting of the part of office cost which was not charged to buying, and about 35 per cent of the managers' salaries, represent 22.6 per cent of the costs of line houses, 7.5 per cent of those of co-operative houses, and 10.0 per cent of those of independent houses. On a hundredweight basis, the comparison is as follows: line, 7 cents; co-operative, 1.6 cents; independent, 2.1 cents. The difference is largely because the line-house organization does its own selling, whereas only 6 of the co-operatives did most of their own selling. The effect of different methods of selling has already been discussed under office and management.

The selling process includes, for a co-operative or independent warehouse doing its own selling, the following: finding buyers; securing cars; looking after the potatoes en route, at inspection points, and at destination; negotiating with buyers after the cars have reached their destination; collecting from buyers; collecting claims against railroads; all correspondence connected with the foregoing; keeping all records connected with the sale; and if the warehouse is using pooling methods, prorating expenses and receipts among the various growers in the pool. For a warehouse consigning to an exchange or commission firm or broker, selling includes only selecting the agent, securing cars, collecting claims against railroads, and negotiating with agents.

Variations in selling cost are also in large part due to differences in volumes handled by various warehouses. The analysis of variations in office and management cost can be applied almost directly to variations in selling cost, as the separation of office and management cost between buying, selling, and supervision was largely made on the basis of very rough estimates. A few of the office costs, however, were charged directly to selling, in particular, market service, telegraph, and advertising and publicity. Most of several miscellaneous items, such as traveling expense and collections, was also charged to selling. Interest cost should vary, as already explained, with methods of selling as well as with methods of buying.

If a warehouse undertakes to do its own selling, this becomes the most important of its functions. Keeping selling costs down in such a case is always important, but not so important as selling to good advantage. Market and telegraph service may be worth all they cost or they may not. Some warehouses could afford to spend more for such service, some are spending too much already. In the first place, a small volume of business will not warrant an elaborate system of news and telegraphic service. In the second place, unless market information is properly used, it may do more harm than good. It is much to be doubted if many local managers are in a position to use market information to much advantage. Using the telegraph in making sales, however, may be well worth while.

It is very clear, from the records, that some of the larger warehouses covered in the survey have developed outlets for their potatoes and are handling their own selling to good advantage.

SIDELINES

The cost of handling potatoes may be somewhat affected by the handling of sidelines. For example, enough flour, feed, and other supplies may be handled to keep the warehouse in use throughout the year; and a manager may be employed on a yearly basis. If the sideline business is important enough, it can properly be made to bear some part of the warehouse costs. It will, in most cases, be proper to charge only that part of management costs to sidelines which is additional because of taking in the sideline business. Working capital may also be put to fuller use by taking on sidelines.

As only 3 of the 71 warehouses handled sidelines to any appreciable extent, it was not possible in this survey to make any analysis of their effect. The procedure followed was to separate the costs directly chargeable to sidelines, and divide salaries and interest between potatoes and sidelines as above indicated.

CENTRAL MARKET COSTS

The principal central market and transportation costs that come out of the net proceeds of a car of potatoes are: freight, brokerage and commissions, inspection fees, car messengering, switching, demurrage, trackage, and a miscellaneous lot of other transportation costs. As already explained, these costs have been omitted from the analysis for two reasons: (1) They are not costs of the local warehouse as such, and (2) the data obtained did not always separate central market costs from deductions due to damage in transit, quality defects, and the like.

Following this procedure does not, of course, give costs on a comparable basis of the locals following different selling practices, as office and management costs are higher for those selling direct to retailers than for those selling on track, and higher for those selling on track than for those consigning to brokers and commission men. It has already been roughly estimated that office and management costs averaged $7 per car higher for those selling direct than for those consigning (see page 52). With this figure may be compared part of the 10 cents per hundredweight, or $36 per car charged by the Minnesota Potato Exchange for its services—only part of it. because the exchange rendered some services not ordinarily performed by a local doing its own selling. It may also be compared with the $13 per car (average for about a thousand cars actually sold) charged by brokers and commission merchants when these agencies did the selling. There is little doubt that local potato warehouses that have developed outlets of their own for their potatoes are able to handle the selling at a lower cost than they can hire it done for them. There is, however, the initial cost of developing such outlets, and the risks involved in dealing with new customers for the first time.

To put the costs of co-operative and independent warehouses on a comparable basis with those of line houses, these charges of $7, $36, or $13 per car must be added to the local cost, for the line houses do all their own selling. Certain other expenses should be added also, such as demurrage, switching, inspection fees, and the like, for these are included in the central office expenses of line houses as given in the tables. These amount to about $2 per car. The central office expenses of line houses as given also include payment to the railway company for preparation of cars ($5 per car) when it was not done by the local warehouses, and payment to the railway company for messengering, car-heating, and all services included when potatoes are shipped under "Option No. 2"—the line houses ship almost altogether on this basis. The charge under this option was $12.30 per car.

LEAST-COST COMBINATION

Obviously no one element of cost can be considered by itself alone. The more spent for equipment, work done (quality being the same) the less the labor required. A conveniently arranged warehouse also reduces the labor required. Given data as to the amount of labor saved by various items of equipment, and as to the cost of equipment and wages of labor, it should be possible to estimate with fair accuracy what equipment it will be economical to install—in other words, determine what combination of labor and equipment will render a given amount and quality of service at the least cost per unit. The data obtained in the survey, however, were not accurate enough to warrant such an analysis.

COST AND AMOUNT OF SERVICE

Throughout the bulletin, it has been obvious that costs of different warehouses have not been comparable because of differences in the amount of service rendered. For example, some warehouses have sold all or most of their potatoes and others have sold few or none. Some have stored more potatoes than others; some have stored for longer periods than others. Some have done the weighing for growers and some have not. Some have provided dumps and some have not. In some cases it has been possible to estimate the difference in costs resulting; in others, not. As a factor in variations in total cost per hundredweight, however, it is one of the most important.

COST AND QUALITY OF SERVICE

In scores of ways, one warehouse may render better service than another, by sorting and grading better, by keeping the potatoes in better condition in storage, by loading cars better, and last and most important of all, by selling for a better price. Obviously no way was possible in this analysis of measuring these differences in quality of service.

ALL COSTS COMBINED

Having analyzed the various elementary costs separately and combined by processes, they can now be combined into total costs per warehouse and per hundredweight. Figure 15 shows the five elements of cost reduced to a hundredweight basis and combined. The office and management cost here included is for co-operatives and independents only—line-house office and management costs include a large element of central office costs arising from selling operations not usually performed by local warehouses. The range with volume of business is from 28.24 cents for houses handling 5000 hundredweight, to 18.57 cents for houses handling 80,000 hundredweight, or a total range of 9.67 cents, or 45.4 per cent of the average of 21.29 cents. The largest absolute range with volume was for building and site cost, at 3.40 cents, with labor next, at 2.80 cents. The percentage range (per cent of the average) was also highest for building and site cost, at 113 per cent, but second for equipment, at 92 per cent. Labor cost is fourth in percentage range, at 48 per cent, and office and management third, at 61 per cent. Figure 15 shows only the absolute range.

It is apparent from the diagram that most of the economies of larger volume of business, so far as warehouse costs are concerned, appear under 30,000 hundredweight, and more than half of them under 20,000 hundredweight. Building and site and equipment are responsible for 3.5 cents of the saving in costs under 20,000 hundredweight, and labor and office and management for 2.7 cents.

Curve A in Figure 16 reproduces the combined curve of Figure 15, and locates the costs for the 38 co-operative and independent warehouses. The absolute range in costs from all causes for co-operative houses is from 15.3 cents for No. 22 to 37.2 cents for No. 7. The absolute range from all causes for independent houses is from 13.3 cents for No. 33 to 31.4 cents for No. 30. Thus the absolute range for both groups is from 13.3 cents to 37.2 cents, or 23.9 cents.

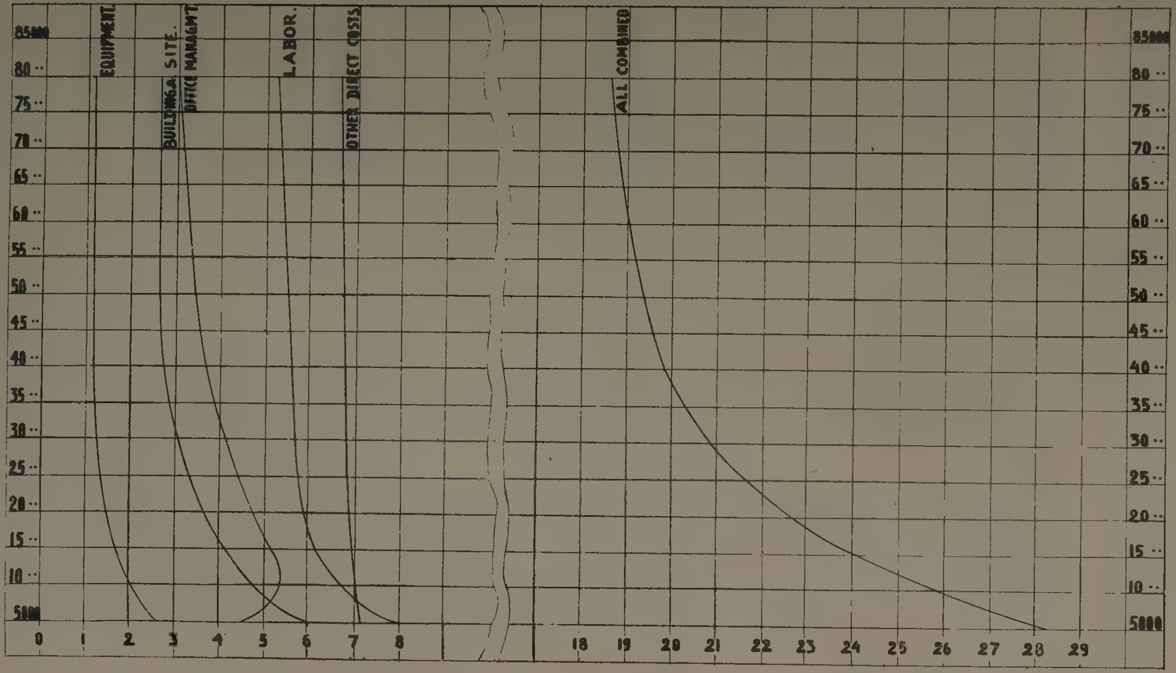

Fig. 15. Elements of Cost Combined According to Volume of Business
The office and management costs given are for co-operative and independent warehouses only.

Volume of business accounts for only 9.67 cents of this. Thus 17.2 cents of it must be due to the other causes that have been pointed out. This is very evident from the diagram. In any volume group—for example, from 15,000 to 25,000 hundredweight—there is a wide range in cost.

It is thus apparent that warehouse costs are very irregular. Some of these irregularities can not be obviated. Any progressing industry is sure to exhibit considerable variation in costs. If none could reduce their costs below those of their competitors, little progress would be made. But it is equally clear that the high costs of many of these warehouses are entirely unnecessary, and could be at least partly eliminated in any season. Others could have been prevented if the warehouse had been properly planned at first. As time goes on, the potato warehouse business will surely be more standardized—warehouses will be more nearly of the same size and construction, with more nearly the same equipment. Also salaries of managers will be more nearly uniform. These standardizations will nearly all be in the direction of lower costs.

Any warehouse manager will do well to calculate his costs for last year's business upon a hundredweight basis and compare his results with the average indicated by Curve A in Figure 16. If he finds that his average is high, he should separate out the various elements making up his total costs and compare each of these with the proper curve in Figure 15. Having discovered which of his costs are high, he can then read carefully the analysis of factors causing variations in that cost, to see if he can discover the causes responsible in his case. Even tho his total costs may be low, he may find that some of his separate costs are high and can be reduced.

As already pointed out, however, he must not conclude in all cases that because certain costs are high he must go about reducing them. It may be that the extra cost is due to extra service or better quality of service rendered, and may be more than warranted.

Curve B in Figure 16 represents the average combined costs per hundredweight for the 33 line houses. It will be remembered that office and management costs of line houses averaged 13.1 cents per hundredweight, as compared with 3.9 cents for other warehouses, and that 72 per cent of these office and management costs were incurred by the central office; and further, that the central office costs were prorated to the locals at a flat rate per hundredweight. Curve B has been adjusted somewhat for the probable error arising from this method. Line house costs are somewhat more regular than those of the other two classes of warehouses, but the extreme range is from 24.9 cents for No. 47 to 46.9 cents for No. 48.

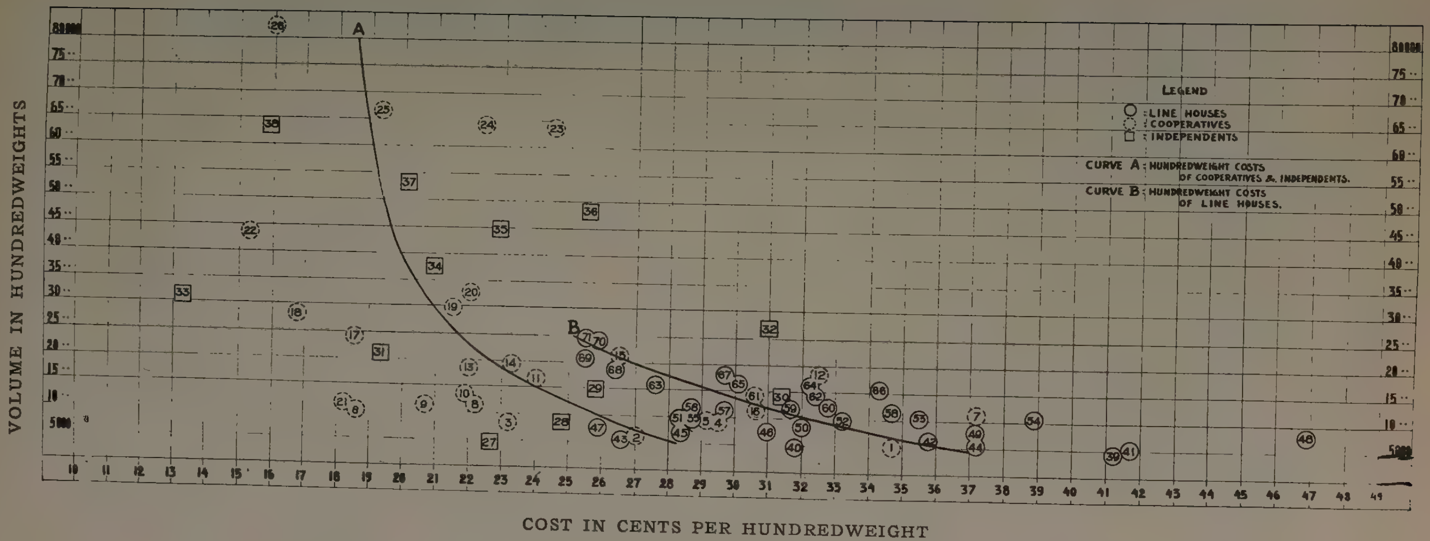

Fig. 16. Relation of Volume of Business to Warehouse Cost per Hundredweight for Co-operative and Independent, and Line Warehouses

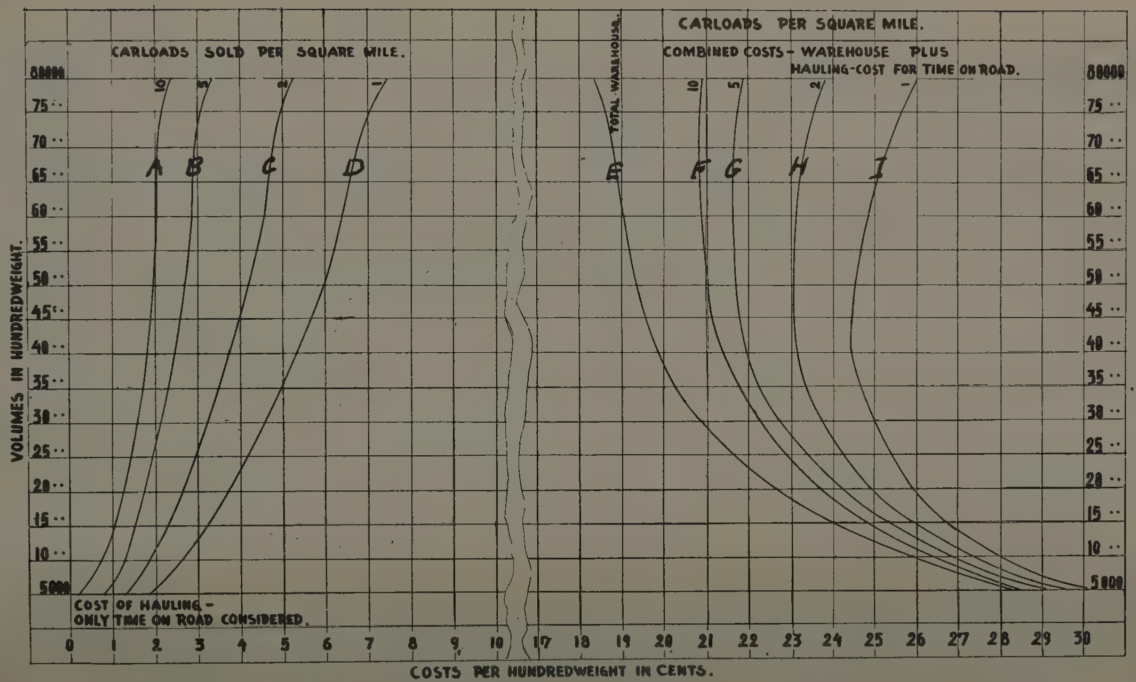

Fig. 17. Hauling Costs

Hauling costs must be considered in determining the most economical size of business. Larger businesses are more economical where production is dense.

SIZE OF WAREHOUSE

The question of the most economical size of warehouse and volume of business must be considered from a community standpoint, rather than from a strictly warehouse standpoint. The larger the volume of business handled at one market place, the farther the potatoes must be hauled and the greater the cost of hauling. The more warehouses at one shipping point, the less business to be handled by each, but perhaps the more convenience in unloading and storing. Figure 17 illustrates the method of analyzing this problem for length of haul and number of warehouses at a shipping point. The length of haul required to obtain a given volume depends upon the density of production. Most potato growing sections in the state range between one and ten carloads per square mile. Clay County averaged over six carloads in 1922. It is impossible to compute accurately any hauling costs for farm products, but one can come as near to a correct figure for hauling potatoes as for any other crop, because some potatoes are actually hauled by special labor hired for the purpose, and most potatoes are hauled at a busy season. Studies made of wage rates for man labor and horse labor employed on Minnesota farms under conditions similar to those prevailing during potato-hauling periods of the year, indicate that 60 cents per hour is somewhere near an average for the farms in most communities. The rates on different farms will probably vary from 40 to 90 cents an hour, depending upon the other farm enterprises combined with potatoes, and the proportions between them, and the supply of labor, as well as upon rates paid for hired labor; but it is probably fairly safe to use an average in this case, as crop combinations will not be greatly different at different distances from the market. Time spent loading and unloading can be ignored as it is a constant amount regardless of the length of haul, except that those living farther away arrive later and are likely to have to wait longer to unload. Hence only time on the road need be considered in the present problem. A rate of travel of three miles per hour has been assumed, and 50 bushels of potatoes to a load. The four curves in the left of the diagram represent hauling costs under these assumptions for time on road only, and for an average haul. The method of computation is as follows:

Commercial production of 5 carloads per square mile:

40,000 cwt.=111.1 carloads (360 cwt.=1 carload).

111.1 carloads will require 22.2 square miles of area.

$\sqrt{\frac{22.2}{3.1416}}$=2.66 mi.=radius of circle with area of 22.2 sq. miles.

2/3×2.66 mi.=1.77 mi.=average length of haul one way for an area 2.66 miles in radius.

2×1.77 mi.=3.55 mi.=length of trip both ways.

$\frac{3.55}{3}$=1.18 hours=time required, at 3 miles per hour.

1.18×\$0.60=\$0.708=average cost of trip, time on road only, at \$0.60 per hour for man and team.

$\frac{\$0.708}{30}$=\$0.0235=cost per cwt. at 30 cwt. per load.

Table L gives the results of such computations for four different densities. It is presumed, however, that persons using this bulletin will make their own assumptions as to density, rate of travel, cost per hour, size of load, and other items.

The foregoing analysis also assumes that one warehouse handles all the business, which is seldom the case. If a given area sells ten carloads per square mile, but has two warehouses which divide the business equally, the results are the same as tho the density were 5 carloads per square mile and one warehouse were handling it. Therefore Curve B would fit rather than Curve A. If there were 5 warehouses in place of one, a more likely assumption, Curve C would fit. It is probable that Curves C and D come nearest to fitting most actual conditions.

Curve E merely reproduces the warehouse cost curve of Figure 15. Curves F, G, H, and I combine Curve E with Curves A, B, C, and D, respectively. It will be noted that if one sold ten carloads per square mile, and delivered at one warehouse, the most economical volume of business would be appreciably above 80,000 hundredweight; and at 5 carloads per square mile it would be somewhere just above 80,000 hundredweight; but according to Curve H, which will more nearly fit most situations in the state, the most economical volume of business would be 50,000 hundredweight. Curve I represents a condition that exists at many shipping points because there are too many warehouses—lowest combined costs around 40,000 hundredweight.

TABLE L

RELATION OF HAULING COSTS TO VOLUME OF BUSINESS FOR DIFFERENT DENSITIES OF COMMERCIAL POTATO PRODUCTION‡

Volume in hundredweight (000's omitted)	10 Carloads§			5 Carloads§			2 Carloads§			1 Carload§		
	Area required	Average haul*	Cost per cwt.†	Area required	Average haul	Cost per cwt.	Area required	Average haul	Cost per cwt.	Area required	Average haul	Cost per cwt.
	Sq. mi.	Mi.	Cents	Sq. mi.	Mi.	Cents	Sq. mi.	Mi.	Cents	Sq. mi.	Mi.	Cents
5	1.4	0.28	0.18	2.8	1.27	0.83	6.9	1.97	1.31	14.0	2.81	1.87
10	2.8	1.27	0.83	5.5	1.96	1.31	13.8	2.81	1.78	28.0	3.96	2.65
15	4.2	1.55	1.41	8.3	2.17	1.44	20.8	3.43	2.28	42.0	4.85	3.24
20	5.5	1.96	1.31	11.1	2.50	1.66	27.8	3.96	2.65	55.0	5.57	3.71
25	6.9	1.98	1.33	13.9	2.80	1.68	34.8	4.43	2.95	69.0	6.24	4.17
30	8.3	2.17	1.44	16.7	3.07	2.04	41.8	4.85	3.24	83.0	6.83	4.56
40	11.1	2.50	1.66	22.2	3.54	2.35	55.5	5.57	3.71	111.0	7.92	5.27
50	13.9	2.80	1.86	27.8	3.96	2.64	69.0	6.24	4.17	139.0	8.95	5.98
60	16.7	3.07	2.04	33.3	4.33	2.88	83.0	6.83	4.56	167.0	9.69	6.38
80	22.2	3.54	2.35	44.4	4.99	3.33	111.0	7.92	5.27	222.0	11.18	7.45

* Both ways.

† Assuming 60 cents per hour for man and team and 30 hundredweight per load, and average rate 3 miles per hour.

‡ Hauling costs are for time on the road only.

§ Per square mile.

If the number of warehouses could be kept to one for 80,000 hundredweight, in an area selling 5 carloads per square mile, the lowest combined cost is 19.8 cents per hundredweight; but if this business is divided among 5 warehouses, the combined cost will be 26 cents per hundredweight. If the commercial production is 2 carloads per square mile, and one warehouse handles it most economically, the combined cost is 21.3 cents per square mile; but if two handle the same volume the combined cost is 23.7 cents per hundredweight.

If, however, a warehouse is to handle 80,000 to 100,000 hundredweight it should be arranged to provide convenient unloading facilities. Moreover, the ratio of potatoes stored to potatoes handled will be low in such a warehouse unless it is built extra large to provide storage, in which case extra building cost will be involved. It is undoubtedly true that the desire to provide storage has been a factor in multiplying the number of warehouses at many shipping points. Line-house organizations, especially, have been actuated by such motives. They find it more economical to store at country stations than in the central market. An analysis to fit a business combining handling and storage on this basis will require data not obtained in the present survey.

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University of Minnesota
Agricultural Experiment Station

Factors Affecting the Price of Minnesota Potatoes

Holbrook Working
Division of Agricultural Economics

UNIVERSITY FARM, ST. PAUL

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University of Minnesota
Agricultural Experiment Station

Factors Affecting the Price of Minnesota Potatoes

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Division of Agricultural Economics

UNIVERSITY FARM, ST. PAUL

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FACTORS AFFECTING THE PRICE OF MINNESOTA POTATOES

By Holbrook Working

INTRODUCTION

Why does the price of potatoes change so much from one year to another? Why does the price of potatoes sometimes change so much during a single season? What is the average change in the price of potatoes from fall to spring? How much are prices affected by an increase of 10 per cent in production? What is a normal production of potatoes for the United States? Everyone who is financially interested in potatoes has asked himself all these questions and many more.

The purpose of this bulletin is to bring together information which helps in answering these questions, and to show as far as possible just what the answers are. The study of the factors which influence the price of potatoes or any other commodity is similar in many ways to the study of the influences which cause disease. Much can be learned about the causes of disease by common observation and without the use of special scientific methods and without any special studies by trained scientists. For example, everyone knows something of the common causes of colds. But it required careful scientific work to determine the cause of tuberculosis; even after it was known that bacteria were responsible for many diseases, only long and careful study made it possible for Robert Koch to demonstrate that tuberculosis was similarly caused by a specific bacterium.

Similarly, everyone knows much about the factors which influence prices, probably more than most people know about diseases. Common observation tells them that when the production is small, the price must be high; and that when other prices are rising rapidly, as they did during the war, the price of potatoes or wheat or any other product is likely to rise also. But only careful study reveals just how much the price will rise when production is decreased 10 per cent, or just how much the price of potatoes will go up on account of some force which is causing other prices to rise.

In the study of prices, as in the study of diseases, we have learned that careful scientific study discloses certain facts that we could not learn by ordinary observation. Many things are still to be learned, but for potatoes we already know just which are the most important factors that ordinarily affect the price, and for five of these factors it has been possible to get statistical measures and to estimate quite accurately what the effect of these factors will be under any given conditions.

Many of the conclusions to be described have already been set forth in a Technical bulletin published in 1922,[1] but since then additional facts have been discovered which more completely explain the movements of the price of potatoes.

PRICES TO BE STUDIED FIRST

The best way to begin a study of the price of potatoes, is by considering the factors which affect the average price for the entire season. Some sections of Minnesota produce considerable quantities of potatoes which are ordinarily marketed in August, but the great bulk of the Minnesota production comes on the market after the first of September. In 1918-19, 13.6 per cent of the carlot shipments moved before the first of September, but for the last four years the average has been 5.1 per cent. Most of the Minnesota crop is usually disposed of by the end of May, only about one per cent being left, on the average, for shipment after June 1. Accordingly the principal interest in Minnesota centers upon the price of potatoes for the nine-month season from September to May.

Table I gives the price of potatoes in St. Paul and Minneapolis for each month from September to May since 1899, and the averages for each season.[2]

Figure 1 shows the average price of potatoes for each season, beginning with 1902-3 and ending with 1923-24. This is what is known as a "ratio chart," being drawn to a scale which gives a fair comparison of *relative* changes. A 10 per cent change, for example, is represented in any part of the chart by the same vertical distance, so that a change in price from 50 to 55 cents looks the same as a change from $2 to $2.20. A chart drawn with the more common arithmetical ruling makes a change from $2 to $2.05 look just as important as a change from 50 to 55 cents, but relatively it is only one quarter as important. The facts which we must consider are clearer if we note the relative changes, hence this ratio scale has been used in all the charts.

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[1] Working, Holbrook. Factors Determining the Price of Potatoes in St. Paul and Minneapolis. Minn. Tech. Bul. 10. 1922.

[2] A detailed description of the method by which these figures were obtained is given in Minn. Tech. Bul. 10, pp. 10-14.

TABLE I

PRICE OF POTATOES PER HUNDREDWEIGHT IN ST. PAUL AND MINNEAPOLIS, MONTHLY, 1899-1923, BY CROP YEARS. AVERAGE TABLE STOCK

	1899-1900	1900-01	1901-02	1902-03	1903-04	1904-05	1905-06	1906-07	1907-08	1908-09	1909-10	1910-11
September	$0.70	$0.43	$1.38	$0.43	$0.80	$0.53	$0.60	$0.70	$0.95	$1.02	$0.77	$1.17
October	0.65	0.43	1.03	0.52	0.80	0.52	0.68	0.67	0.85	0.98	0.67	0.98
November	0.73	0.48	1.23	0.57	0.90	0.50	0.88	0.63	0.77	0.95	0.65	0.80
December	0.85	0.62	1.27	0.62	0.95	0.50	0.87	0.58	0.77	1.02	0.63	0.73
January	0.67	0.60	1.22	0.68	1.03	0.80	0.83	0.68	0.87	1.10	0.68	0.82
February	0.67	0.75	1.17	0.65	1.47	0.45	0.77	0.65	0.97	1.28	0.75	0.80
March	0.57	0.67	1.20	0.58	1.62	0.48	0.68	0.75	1.03	1.42	0.58	0.87
April	0.42	0.58	1.35	0,53	1.70	0.38	0.88	0.82	1.02	1.62	0.37	1.05
May	0.37	0.73	1,22	0.70	1.53	0.43	0.87	0.95	0.95	1.52	0.42	1.05
Annual average*	$0.62	$0.58	$1.23	$0.58	$1.20	$0.52	$0.78	$0.72	$0.90	$1.20	$0.60	$0.92
Harmonic mean	$0.58	$0.57	$1.23	$0.58	$1.10	$0.50	$0.77	$0.70	$0.90	$1.17	$0.58	$0.90

	1911-12	1912-13	1913-14	1914-15	1915-16	1916-17	1917-18	1918-19	1919-20	1920-21	1921-22	1922-23	1923-24
September	$1.23	$0.68	$1.05	$0.95	$0.55	$1.87	$1.78	$2.10	$2.57	$1.98	$1.98	$0.87	$1.12
October	0.97	0.62	1.02	0.72	0.78	2.03	2.30	1.83	2.43	1.65	1.70	0.76	0.88
November	1.13	0.70	1.02	0.57	0.85	2.52	1.97	1.62	2.65	1.77	1.47	0.70	0.81
December	1.17	0.67	0.98	0.62	1.07	2.47	1.78	1.60	3.05	1.30	1.38	0.64	0.85
January	1.45	0.65	1.00	0.65	1.50	2.78	1.98	1.77	3.98	1.20	1.73	0.62	1.12
February	1.62	0.67	1.00	0.70	1.43	3.60	2.02	1.68	4.05	0.92	1.58	0.62	1.07
March	1.86	0.65	1.03	0.65	1.38	3.75	1.73	1.48	5.28	1.02	1.43	0.86	1.03
April	1.98	0.60	1.05	0.70	1.32	4.27	1.07	1.92	7.02	0.82	1.32	1.08	1.15
May	1.85	0.68	1.08	0.68	1.43	4.63	1.05	2.02	7.13	0.73	1.65	0.84	1.08
Annual average*	$1.47	$0.65	$1.02	$0.70	$1.15	$2.97	$1.75	$1.78	$4.20	$1.25	$1.58	$0.78	$1.14
Harmonic mean	$1.38	$0.65	$1.02	$0.68	$1.03	$2.82	$1.63	$1.77	$3.63	$1.13	$1.56	$0.75	$1.00

* Weighted average obtained by weighting monthly prices by the number of weeks included in each.

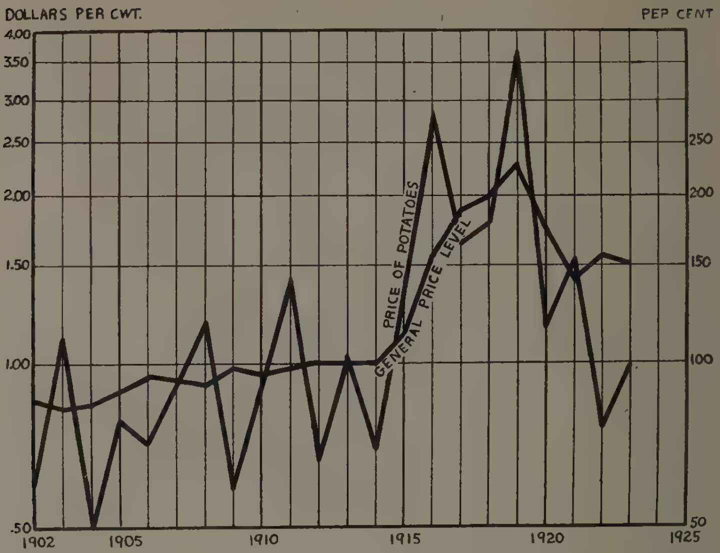

Fig. 1. Changes in Price of Potatoes and General Price Level
The price of potatoes goes up and down with the general price level.

FACTORS AFFECTING AVERAGE PRICE FOR THE SEASON

1. VALUE OF THE DOLLAR

The first factor which must be considered is the value of the dollar. Everybody knows that the value of the dollar changes. During 1919 and part of 1920 it fell to a point where on the average a dollar would buy only one half to one third of what it would during the years just before the war; in other words, prices were two or three times as high as before the war. During 1920 the value of the dollar rose very suddenly, which is just another way of saying that prices fell very rapidly, so that now a dollar will buy on the average about two thirds of what it would before the war.

Of course when discussing the changes in the value of the dollar or in the price level, one is really not talking of *causes* but of effects. We know pretty well what these causes are, but in studying their effects on any one product, the most accurate way is to take the average of the changes of a large number of different commodities as measured by price index numbers. Thus it is convenient to speak of the changes in the value of the dollar as causing the changes in the price of potatoes and to measure the influence by means of price index numbers.

Besides showing the changes in the price of potatoes, Figure 1 shows also the changes in the value of the dollar as measured by an index number of prices of "all commodities" as calculated by the United States Bureau of Labor Statistics from prices of about 400 different commodities representing practically every kind of goods sold in the United States. The figures for the index number are given in Table II. It is easy to see that the price of potatoes moves more or less in the same way as this index number made up from an average for 400 different commodities.

TABLE II

General Price Level, 1902-3 to 1923-24*
(Average for 1913=100)

1902-03	85.0
1903-04	83.7
1904-05	84.2
1905-06	89.0
1906-07	94.7
1907-08	92.7
1908-09	91.7
1909-10	97.6
1910-11	95.6
1911-12	97.5
1912-13	99.6
1913-14	99.3
1914-15	99.3
1915-16	111.0
1916-17	152.5
1917-18	185.8
1918-19	199.9
1919-20	227.5
1920-21	173.0
1921-22	141.7
1922-23	156.3
1923-24	150.8

* Harmonic mean of nine months, October to June, for 1902-14; September to May for 1915-23. Bureau of Labor Statistics "all commodities" index number, unweighted, 1902-12; 1919 weights, 1913-22.

From Figure 1, however, it is apparent that the changes in the value of the dollar explain only a part of the changes in the price of potatoes. This brings us to a very important step in the method to be used. Having found one cause of changes in the price of potatoes, we must *remove the changes due to that cause,* and then it will be easier to see just what changes remain to be explained. This is a step which will be repeated with every new factor discovered.

The effect of the changes in value of the dollar can be removed by dividing the price of potatoes by the index number of the general price level, which seems to be the best measure of the way the changes in the value of the dollar affect the price of potatoes. The result is shown in Figure 2. We may call this a chart of the *real value* of potatoes or, for brevity, merely the *value* of potatoes. The average price level of 1913 is taken as 100 per cent and all changes are measured from that point. If the price of potatoes were $1 per hundredweight during a season in which the price level was 100 per cent, we should say that the *value* of potatoes was $1 per hundredweight. But if the price of potatoes were $1 per hundredweight during a season in which the price level was 200 per cent, we should say that the *value* of potatoes was only 50 cents per hundredweight.

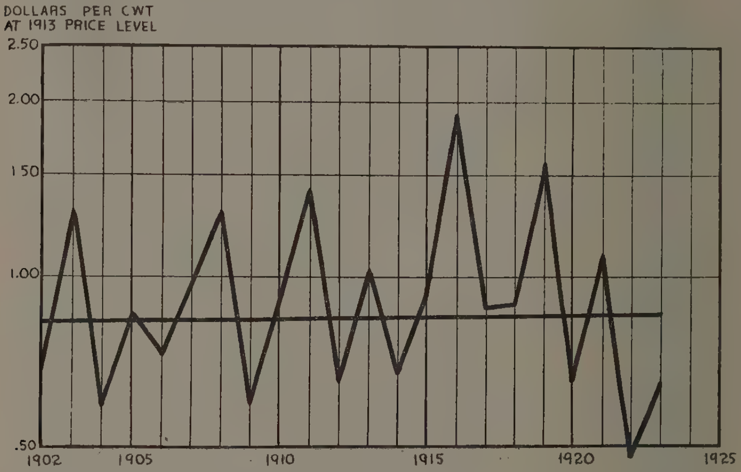

Fig. 2. Changes in Price of Potatoes with Effect of First Factor Removed

After making allowance for the changes in the general price level, the first factor considered, the price of potatoes still shows wide fluctuations from one year to another.

The most important facts to be noticed about Figure 2 are that fluctuations are somewhat smaller and that the changes after 1915 look more like the changes before 1915 than in the original chart of the price of potatoes (Fig. 1). This is the result of removing the effect of the first factor, the changes in the value of the dollar.

2. TREND OF THE VALUE OF POTATOES

Examination of Figure 2 suggests that there has been a gradual increase in the value of potatoes during the period covered, or at least up to 1919. Taking the period as a whole, the prices of potatoes have been rising a very little more than the prices of most other commodities, and when the value of potatoes is measured in terms of goods in general it shows a slight upward trend, as represented by the "normal" line. The change in this normal is not great, but its effects must be removed, just as the effects of the changes in value of the dollar were removed in order to determine how completely the changes in the price of potatoes are explained by these factors and the remaining factors to be considered. In removing the effect of the changing normal value of potatoes, it is necessary to express the remaining fluctuations in terms of *percentages of normal* instead of in dollars. The result is shown in Figure 3, which looks exactly like Figure 2 except that the curve showing the fluctuations in the price of potatoes has a horizontal trend and is higher in the chart; and the scale is given in percentages of normal instead of in dollars. The changes are almost as great after removing the effects of this second factor as before.

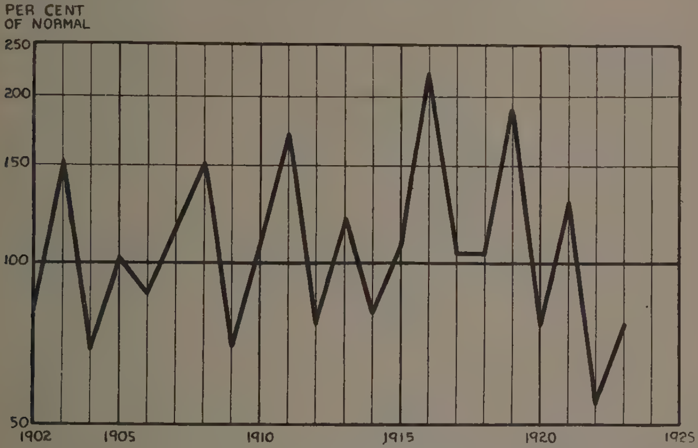

Fig. 3. Changes in Price of Potatoes with Effect of First and Second Factors Removed

The second factor considered is the change in the normal value of potatoes. Taking account of this factor makes only a slight change in the appearance of the price curve here as compared with that in Figure 2.

3. FLUCTUATIONS IN PRODUCTION OF POTATOES

Everyone knows that changes in the production of potatoes result in changes in price. When the crop is large the price must be low or they cannot all be sold; and when the crop is small, consumers are willing to pay a high price for what they can get. Of course, if anyone had a monopoly on most of the potatoes raised, it would pay to hold the price high even if the crop were large and let all the potatoes not used go to waste; but as it is, no producer or group of producers is willing to let his potatoes go to waste while all other producers sell their potatoes at a high price. Even if a single co-operative organization could get control of as large a proportion of the potatoes raised in the United States as the Sun Maid Raisin Growers' Association has of the raisins, they could not set the price so high as to cause large quantities of potatoes to go to waste, without being condemned by the courts as a monopoly.

While everybody knows that when the crop is large the price must be low in order to have the potatoes used, not everyone knows or remembers that much of the extra crop is used on the farm and can best be used there. When the crop is large, it never pays to ship small and inferior potatoes to market; it is much better to keep them on the farm and feed them to hogs or cattle.

TABLE III

TWENTY-SEVEN LATE CROP STATES*

1 Maine
2 New Hampshire
3 Vermont
4 Massachusetts
5 Rhode Island
6 Connecticut
7 New York
8 New Jersey
9 Pennsylvania
10 West Virginia
11 Ohio
12 Indiana
13 Illinois
14 Michigan
15 Wisconsin
16 Minnesota
17 Iowa
18 North Dakota
19 South Dakota
20 Nebraska
21 Montana
22 Wyoming
23 Colorado
24 Idaho
25 Washington
26 Oregon
27 California

* States usually making over half their potato shipments after the first of September.

While many people think of the production of potatoes for the entire United States as affecting the price for the late crop, this is not entirely true. It is only the part of the production which is available for use after the first of September that affects the price after the first of September. There are 27 states which make over half of their potato shipments after the first of September, as listed in Table III. While the production in these 27 states is not an entirely accurate indication of the total crop available for use after the first of September, owing to the fact that considerable quantities of potatoes are shipped out of these states before September, while states farther south continue shipping after that date, it is the best available figure on late crop production. Table IV, compiled from the reports of the United States Department of Agriculture with certain revisions in the acreage figures, shows the acreage, average yield per acre, and production for the 27 late crop states since 1902.

A crop of 300,000,000 bushels for these 27 states, which would have been a very large production in 1902, would be considered small now. In judging whether a crop is large or small, it must be considered in relation to a normal production which increases from year to year, allowing for the increase in population of the country and changes in consumption habits. The usual way of calculating a normal when it is not changing from year to year is to take an average. Fortunately, mathematical methods[3] have been worked out for calculating a sort of average which allows for a regular change from year to year. Instead of a single value, this gives a series of values, and when they are plotted on a chart, a line may be drawn through them as shown by the line marked "normal" in Figure 4. The same method was used in calculating the "normal" value of potatoes shown in Figure 2.

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[3] The most commonly used of these methods is called the "method of least squares." It is really not a method, but a principle, which is applied in various ways to suit different cases. As applied in the simplest cases, it is familiar to everyone, being merely the ordinary average.

TABLE IV

Acreage, Production, and Average Yield per Acre of Potatoes in Twenty-seven Late Crop States, 1902-24

Year	Acreage	Yield per acre	Production
	Thousands of acres	Bushels	Millions of bushels
1902	2621	96.0	251.6
1903	2567	87.1	223.6
1904	2629	115.2	302.8
1905	2575	88.1	226.8
1906	2558	105.9	271.0
1907	2622	98.4	258.1
1908	2686	86.6	232.6
1909	2874	111.1	319.3
1910	2841	96.5	274.2
1911	2797	88.4	247.3
1912	2907	118.5	344.5
1913	2866	94.8	271.7
1914	2910	119.5	347.7
1915	2932	94.8	278.0
1916	2771	78.5	217.5
1917	3079	103.6	318.9
1918	2998	100.5	301.3
1919	2950	93.0	274.5
1920	2967	114.6	340.0
1921	3169	95.5	302.5
1922	3470	110.1	381.9
1923	3021	115.1	347.7
1924	2829	132.3	374.3

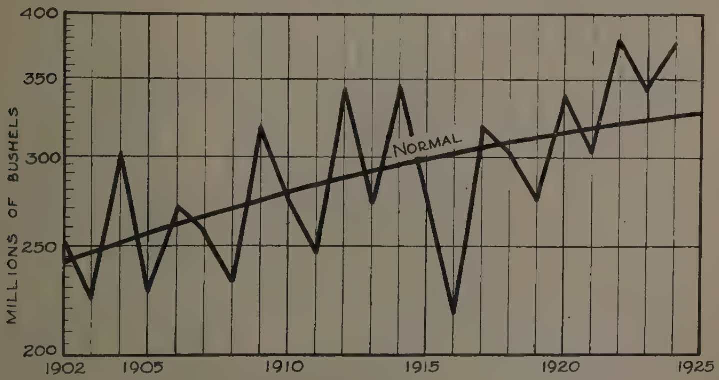

Fig. 4. Production of Potatoes in Twenty-seven Late Crop States

The normal production of potatoes is increasing about 3,400,000 bushels a year, but the actual production varies greatly above and below this normal. Comparison with Figure 3 will show that there is a close correspondence between the changes in production and the changes in price.

The relationship between production and price can be seen quite clearly by arranging the years in the order of the size of the late crop (relative to normal) as in Figure 5 and drawing a vertical bar for each year having a height proportional to the price, after correcting the price for the effects of changes in the value of the dollar and for its trend.

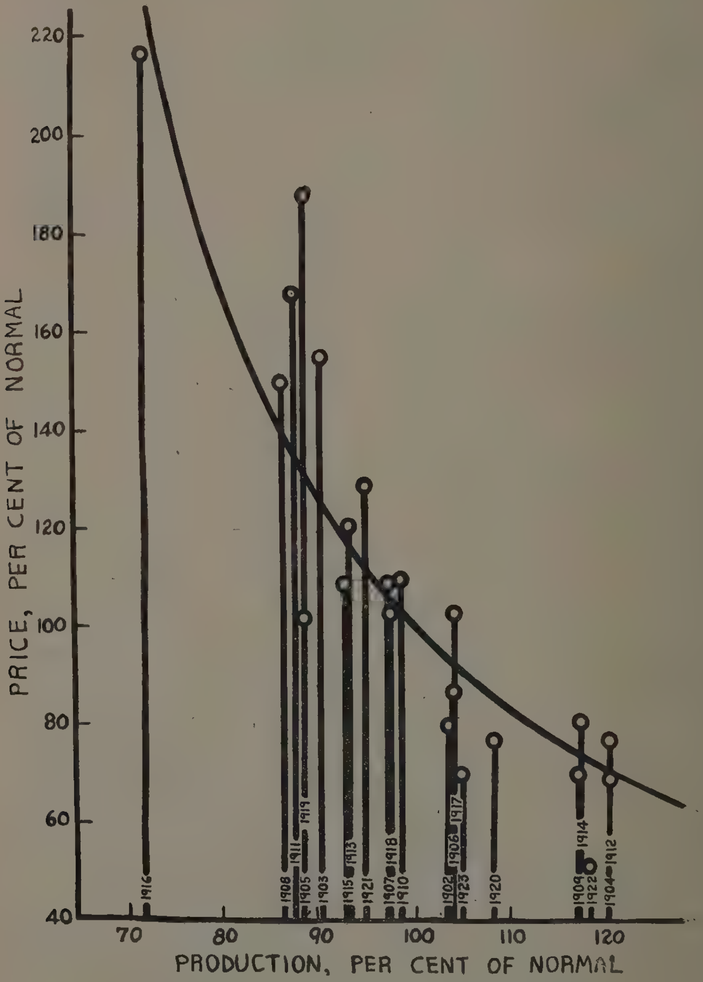

Fig. 5. Relation of Production and Price of Potatoes

When the production of potatoes is small the price tends to be high and when the production is large the price tends to be low. In 1916 the production was only 72 per cent of normal and the price was 217 per cent of normal; in 1912 the production was 120 per cent of normal and the price was 77 per cent of normal. Even in years of almost the same relative production, the price may vary considerably, as between 1902, 1906, 1917, and 1923. The curved line shows the average relationship between production and price.

It might be expected that when the same relative production was found in more than one year, the price would be the same in those years; but when it is remembered that there are other factors affecting price, it is clear that the price is likely to differ even between years when the relative production is the same. The price figures used in Figure 5 have already been corrected for the changes in the value of the dollar, but there are still other important factors which affect the price.

If we had figures for many years, we could pick several years in which the production was 5 per cent above normal, calculate the average price for those years, and thus get a good idea of the effect of a production 5 per cent above normal. Then we could take several years in which the production was 10 per cent above normal and find the average effect of that production; and so on. We cannot get figures for enough years to do this, but there is another way of getting almost the same result. When it was necessary to get an "average" production which showed the way in which the average was changing from year to year, we used the method of least squares. The method of least squares can also be used to get an average price which shows the way in which the average changes with changing production. The line drawn through the dots in Figure 5 shows the way in which price may be expected to vary with changing production as determined by this method. The results may be described briefly as follows:

When production is above normal (per cent)	Price will probably be below normal (per cent)
20	29
10	17
0	0
below normal	above normal
10	26
20	70

The normals from which these percentages should be figured for the next three years may be obtained from Table V.

TABLE V

NORMAL PRODUCTION IN TWENTY-SEVEN LATE CROP STATES AND NORMAL VALUE OF POTATOES IN ST. PAUL AND MINNEAPOLIS, 1925-27

Year	Normal production	Normal value per cwt.*
	Millions of bushels	Cents
1925	334.9	85.3
1926	338.3	85.4
1927	341.7	85.4

* At 1913 price level. Multiplying these figures by the price level index number for the year gives the normal *price* of potatoes for that year.

Having found the relation between price and production, it is possible to remove the effect of changing production, just as the effect of the changing value of the dollar and the effect of the trend of the value have already been removed. The result is shown in Figure 6. By comparing Figure 6 with Figure 1, it will be seen that the three factors which have been considered—value of the dollar, trend, and production—explain a large part of the fluctuation in the price of potatoes, for after the effect of these factors has been removed, only a relatively small proportion of the original fluctuation remains.

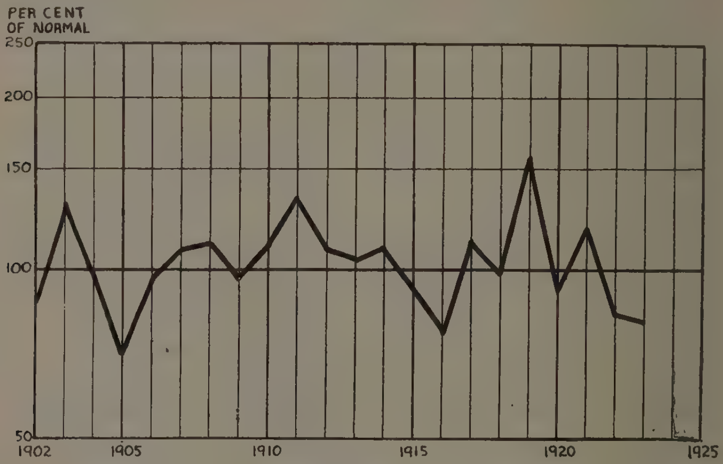

Fig. 6. Changes in Price of Potatoes with Effect of First, Second, and Third Factors Removed

The third factor is production in the late crop states. After making allowance for the changes in production as well as for the changes in general price level and normal value, the changes shown still remain to be explained.

4. PRICE OF POTATOES IN AUGUST

The effect of the price of potatoes in August on the price later in the season is indirect and would not have to be considered at all if we knew the quantity of potatoes actually available for use after the first of September. But in getting figures on the size of the crop, the best that can be done is to take the total production for the states that put more than half their crop on the market after the first of September. If the price of potatoes is high during August, a considerable part of the crop of these states will be put on the market before the first of September; while if the price is low during August, more of the crop will be left for sale after the first of September. Accordingly a high price in August will tend to increase the price later in the season, and a low price in August to decrease the price later in the season. The lateness of the season has an effect also, but no means has yet been worked out for measuring it.

The price of potatoes in August in St. Paul and Minneapolis is not a good indication of the price over most of the area which ships large quantities of potatoes in August, hence it is better to take the price of potatoes in New York City, which is the most representative market. The figures used are shown in Table VI. In estimating the effect of the price in New York in August, it is necessary to consider its relation to the normal price in August, just as it was necessary to consider the relation of production to its normal. The ratio of the actual price of potatoes in August, in New York City, to its normal may be obtained by first correcting for the change in the value of the dollar, thus obtaining the value of potatoes in August, and then calculating the trend of the value, as was done with the price of potatoes in St. Paul and Minneapolis, and taking the ratio of the actual value to the normal given by this trend. When this is done, it is found that for every 1 per cent that the price in New York in August diverges from its normal, the price of potatoes in St. Paul and Minneapolis for the season from September to May will diverge three tenths of 1 per cent from its normal.[4] The normal values of New Jersey Giants and Cobblers in New York in August for the next three years are shown in Table VII.

TABLE VI

AVERAGE PRICE OF NEW JERSEY GIANTS AND COBBLERS IN NEW YORK CITY IN AUGUST, PER 150-POUND SACK, 1902-24

Year	Price
1902	$1.01
1903	1.57
1904	1.28
1905	1.42
1906	1.26
1907	2.09
1908	2.31
1909	1.92
1910	1.74
1911	2.79
1912	1.80
1913	1.93
1914	1.80
1915	1.06
1916	2.48
1917	3.12
1918	3.88
1919	4.86
1920	3.22
1921	3.90
1922	1.40
1923	3.64
1924	1.90

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[4] This is as accurate a statement as can be given without taking account also of the size of the late crop. When the late crop is small, a 1 per cent variation in price in August has more effect than when the late crop is large. The only satisfactory way to take account of this is by the use of the formulas given on p. 37.

TABLE VII

Normal Values of New Jersey Giants and Cobblers in New York City in August, 1925-27, Dollars per 150-Pound Sack*

Year	Value
1925	1.59
1926	1.58
1927	1.57

* At the 1913 price level. Multiplying these figures by the price level index number gives the *normal price* for the year.

Making use of this knowledge, we may now remove the effects of the price in August. The result is shown in Figure 7.

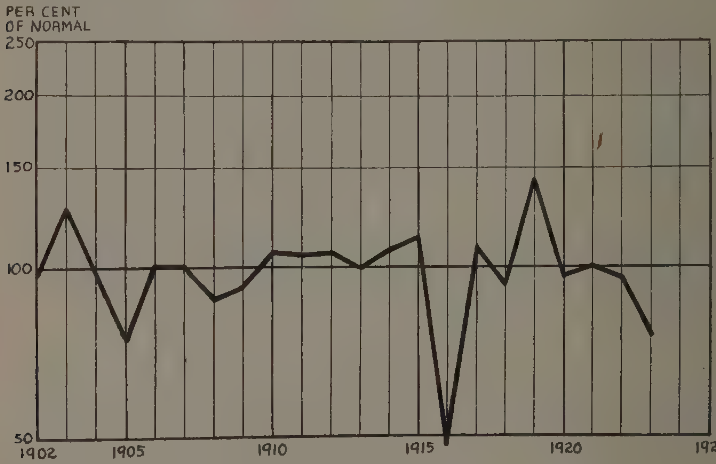

Fig. 7. Changes in Price of Potatoes with Effect of First Four Factors Removed

The fourth factor is price in August. The first four factors explain most of the changes in the price of potatoes, but the price was considerably higher in 1903 and 1919 and lower in 1905, 1916, and 1923 than can be accounted for by these factors alone.

5. VARIATION IN QUALITY

Another factor which influences the price of potatoes is variation in quality. In some years the quality of Minnesota potatoes averages very high, in other years, low. No absolute standards of quality have ever been worked out for potatoes, partly because it is so difficult to define what constitutes good quality and partly because opinions as to quality differ. The only reliable basis for judging quality is a knowledge of what consumers want and for what they will pay.

The best way to determine the effect of the quality of potatoes seems to be to compare the prices at which Minnesota potatoes are selling with those of other potatoes. The comparison should be made with the prices of potatoes from various other districts, or with the average price of potatoes from a large district, in order to be sure that an unusually favorable price for Minnesota potatoes, for example, is really the result of good quality in the Minnesota potatoes and not merely of poor quality in those with which they are compared.

The best measure of quality found for statistical purposes, when it is necessary to have figures back to 1902, is the difference between the price of Minnesota potatoes in St. Paul and Minneapolis and the price of what are known as "Maine" and "State and Western" potatoes in New York City, in November or later. This difference must be compared with the normal difference, which varies with changes in freight rates and changes in the price level. The difference is affected also by the size of the late crop and the percentage of the crop produced in the western states. This renders the comparison rather difficult, and many people may prefer to base their own conclusions on a study of the prices of Minnesota potatoes in comparison with those of other potatoes in markets where both are sold side by side.

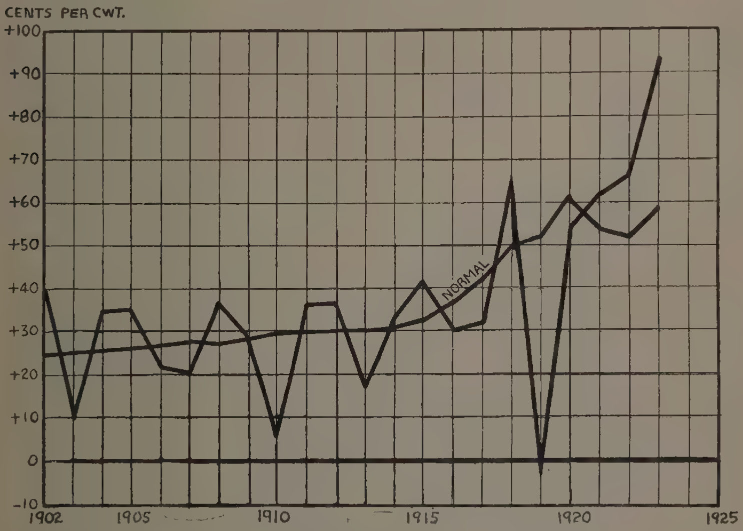

Fig. 8. Difference between Price of Potatoes in St. Paul and Minneapolis and Price in New York City

New York prices are on Maine and New York State potatoes. Taking the average of the potatoes from these two states together, the quality usually does not change greatly from year to year. When the difference is small or even in favor of Minnesota, as in 1919, it is a good indication of unusually high quality in Minnesota potatoes. When the difference is above normal, as in 1923, it is a good indication of unusually poor quality in Minnesota potatoes. After making allowance for certain other factors affecting the difference, an excellent indication of changes in quality is given.

If it is desired to judge the quality of Minnesota potatoes by a comparison of the price of Minnesota potatoes in St. Paul and Minneapolis with the price of "Maine" and "State and Western" potatoes in New York City, the formula given on p. 39 may be used. This formula applies specifically to the difference in November, but is usually quite accurate for any date after the first of November. Before the first of November, the difference is not a very reliable indication of the difference in quality. Figure 8 and Table VIII show the fluctuations in this difference for November of each year since 1902 and the normal difference for each year.

TABLE VIII

PRICE OF POTATOES PER HUNDREDWEIGHT IN ST. PAUL AND MINNEAPOLIS AND IN NEW YORK CITY, NOVEMBER AVERAGE, 1902-24

Year	Price		Actual Difference	Normal Difference‡
	In St. Paul and Minneapolis*	In New York City†		
1902	$0.57	$0.97	$0.40	$0.26
1903	0.90	0.98	0.08	0.26
1904	0.50	0.85	0.35	0.26
1905	0.88	1.23	0.35	0.26
1906	0.63	0.85	0.22	0.27
1907	0.77	0.97	0.20	0.28
1908	0.95	1.32	0.37	0.28
1909	0.65	0.93	0.28	0.28
1910	0.80	0.85	0.05	0.29
1911	1.13	1.50	0.37	0.29
1912	0.70	1.07	0.37	0.30
1913	1.02	1.18	0.16	0.30
1914	0.57	0.90	0.33	0.30
1915	0.85	1.27	0.42	0.32
1916	2.52	2.82	0.33	0.36
1917	1.97	2.23	0.26	0.41
1918	1.62	2.28	0.66	0.49
1919	2.65	2.62	−0.03	0.51
1920	1.77	2.30	0.53	0.61
1921	1.47	2.08	0.61	0.54
1922	0.70	1.37	0.67	0.52
1923	0.81	1.77	0.96	0.59
1924	0.68	1.16	0.48	0.59

* Prices apply to average quality Minnesota potatoes, table stock.

† U.S.D.A. Yearbook, 1922, page 676, supplemented by information supplied by the U.S. Bureau of Agricultural Economics. Prices apply to "Maine" and "State and Western" table stock.

‡ The "normal" difference is given by the equation:

Normal difference (cents) $= 0.0474L + 0.00335tL + 0.891F$

Where L = price level, $(1913 = 100)$;

t = time, measured in years from 1900;

F = freight rate in cents per hundredweight, as shown in Table IX.

TABLE IX

Freight Rate per Hundredweight on Potatoes in Car Lots from St. Paul or Minneapolis, 1902-24*

Year	To Cincinnati	To Pittsburgh	Mean
	Cents	Cents	Cents
1902	22.0	25.0	23.5
1903	22.0	25.0	23.5
1904	22.0	25.0	23.5
1905	22.0	25.0	23.5
1906	22.0	25.0	23.5
1907	22.0	25.0	23.5
1908	22.0	25.0	23.5
1909	22.0	25.0	23.5
1910	22.0	25.0	23.5
1911	22.0	25.0	23.5
1912	22.0	25.0	23.5
1913	22.0	25.0	23.5
1914	22.0	25.9	23.9
1915	23.1	26.3	24.7
1916	23.1	26.3	24.7
1917	23.1	26.3	24.7
1918	29.0	33.0	31.0
1919	29.0	33.0	31.0
1920	38.5	44.0	41.5
1921	38.5	44.0	41.5
1922	34.5	39.5	37.0
1923	41.5	47.5	44.5
1924	41.5	47.5	44.5

* Rates in force in November of each year.

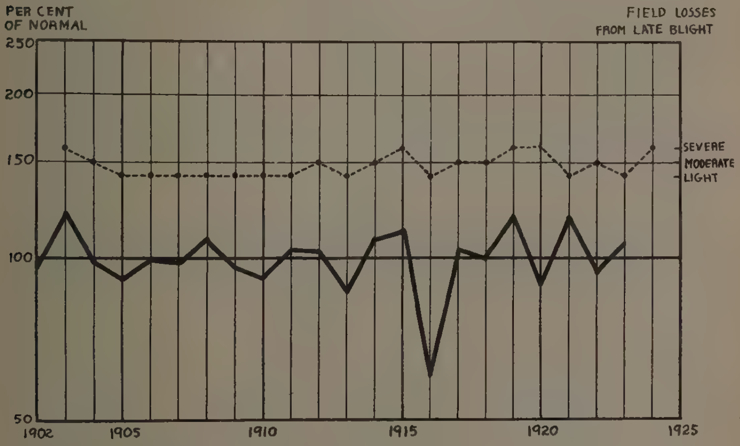

Fig. 9. Changes in Price of Potatoes with Effect of Five Factors Removed

The fifth factor is variation in quality. The five factors together explain most of the changes in the price of potatoes, as may be seen by comparing the changes shown in Figure 1 with those that remain after allowing for the effects of the five factors, as shown here. Losses from late blight rot will explain part of the remaining changes. When late blight is heavy, there is usually a good deal of rot in storage and the price of good potatoes goes up.

The extent to which the actual price in 1916 fell below the expected price suggests an underestimate of the production for that year, indicated also by a study of Figure 12.

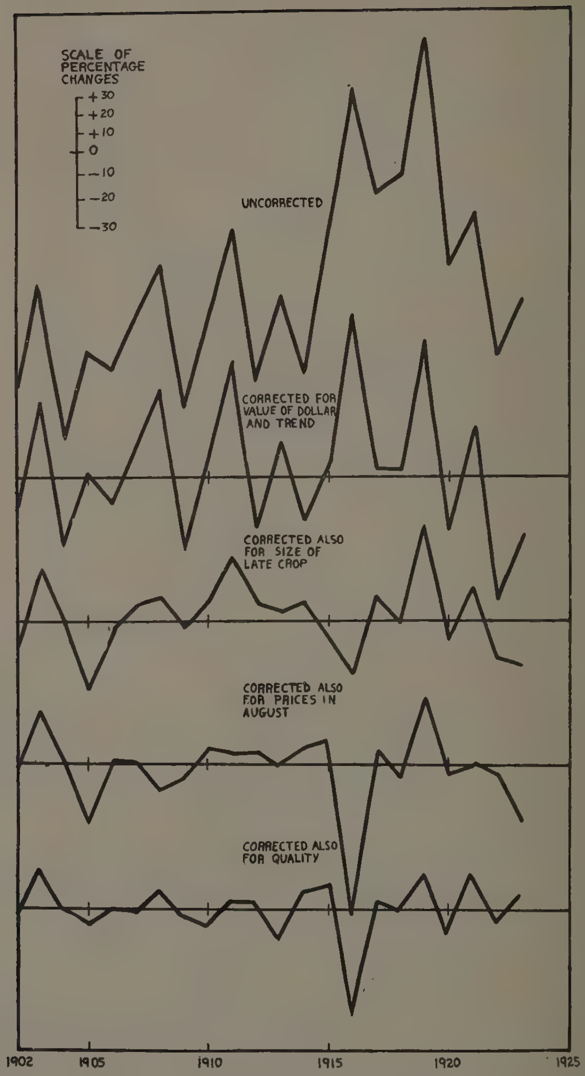

Fig. 10. Changes Remaining To Be Explained at Successive Stages in the Study

When the curves shown in the preceding charts are brought together, it is easy to see that each factor considered has helped to explain the changes which actually occur. The top curve shows the actual changes in the price of potatoes; the second curve, the changes which remain to be explained after allowing for the effect of changes in the general price level and in the normal value of potatoes; the lower curves, the changes remaining after allowing also for the effects of the third, fourth, and fifth factors, respectively. Most of the changes in the top curve are accounted for by the five factors, but some still remain in the last curve.

If the variations in quality of potatoes are determined in this way and their effects removed, the fluctuations which remain are those shown in Figure 9. As this is the last of the factors determining the changes in the price of potatoes from one year to the next for which it has been possible to get a measure, it is interesting to note how far we have gone in explaining the changes which actually occur in the price of potatoes from one year to another. Figure 10 shows the curves of five preceding charts brought together for comparison. The top curve shows the actual changes in the price of potatoes; the second, the changes which remained after removing the effects of the first two factors considered, namely the changes in the general price level, and of the upward trend in the real value of potatoes. The remaining curves show the changes which remain unexplained after removing successively the effects of changes in production in the late crop states, of changes in the price in August, and of changes in quality. The changes which remain unaccounted for, as indicated by the last curve on the chart, are relatively small compared with those shown in the first curve.

Another way to make the comparison is to show the changes which actually occurred as compared with the changes which would have occurred if the price had been affected only by the five factors whose effect has been measured. Table X gives the actual price, the "calculated price" (obtained by taking account of the five factors which have been considered), and the percentage difference between the two. The comparison is made graphically in Figure 11.

TABLE X

CALCULATED AND ACTUAL PRICE OF POTATOES PER HUNDREDWEIGHT IN ST. PAUL AND MINNEAPOLIS, NINE-MONTH AVERAGE, SEPTEMBER TO MAY, 1902-23

Year	Calculated price	Actual price	Per cent difference
1902-03	$0.61	$0.58	− 6
1903-04	0.96	1.10	+15
1904-05	0.51	0.49	− 4
1905-06	0.84	0.77	− 8
1906-07	0.72	0.70	− 3
1907-08	0.93	0.90	− 3
1908-09	1.10	1.17	+ 7
1909-10	0.61	0.58	− 5
1910-11	0.98	0.90	− 8
1911-12	1.35	1.39	+ 3
1912-13	0.63	0.66	+ 4
1913-14	1.14	1.02	−10
1914-15	0.62	0.68	+ 9
1915-16	0.92	1.03	+11
1916-17	3.33	2.82	−16
1917-18	1.58	1.63	+ 3
1918-19	1.76	1.76	0
1919-20	3.28	3.64	+11
1920-21	1.29	1.13	−12
1921-22	1.35	1.56	+16
1922-23	0.83	0.75	−10
1923-24	0.90	1.00	+11

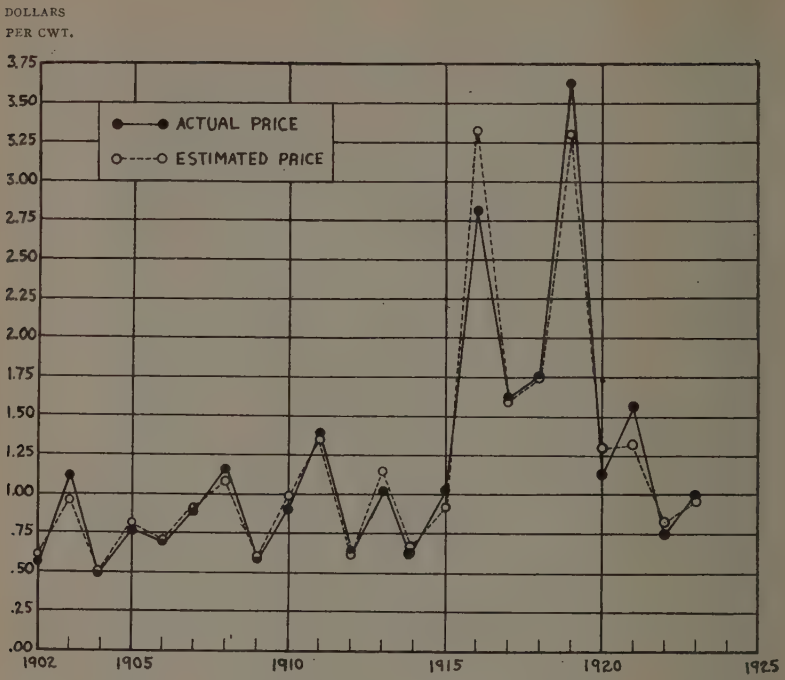

Fig. 11. Actual and Estimated Prices of Potatoes, 1902-23

The hollow circles connected by the dotted lines show what the price would have been each year since 1902 if it had been affected by these five factors only. The solid circles show what the price actually was. The five factors explain most of the changes in the price of potatoes.

It is noticeable that the differences between the calculated prices and the actual prices are greater since 1916 than in earlier years. This may be due to increased difficulty in getting reliable production figures. There has been considerably more fluctuation in acreage of potatoes in recent years than previously and the United States Department of Agriculture finds it very difficult to get accurate estimates of these changes in acreage. Errors in the acreage figures result in corresponding errors in the production figures and any error in the production estimates results in about twice as great an error in the calculation of the price which will move the crop. For example, Figure 12 shows the estimated acreage for 1916 considerably below the acreage for 1915.[5] If this estimate for 1916 was too low, then the price calculated from the production figures for that year would have been too high. This may be the explanation of the fact that the calculated price for 1916 was considerably above the actual price.

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[5] Data from Table IV.

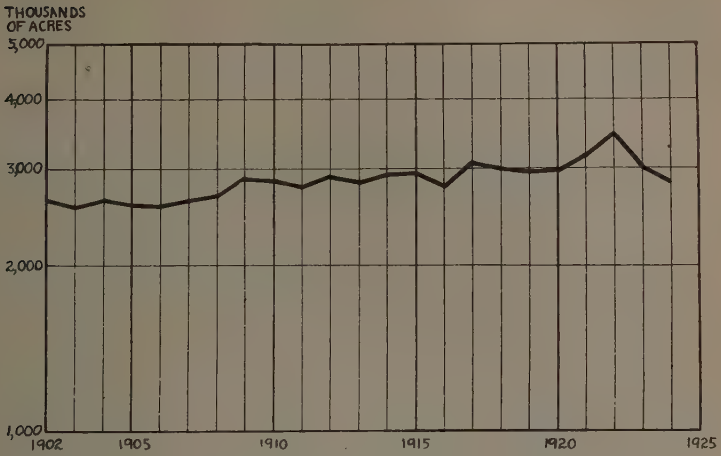


Fig. 12. Acreage of Potatoes in Twenty-seven Late Crop States, 1902-24

The acreage of potatoes usually does not change much from year to year except for a steady increase. This fact opens to question the drop in acreage shown for 1916. In recent years, however, the changes have been greater owing to the readjustments of the post-war years.

6. LOSS IN STORAGE

One other important factor is known to influence the price of potatoes, namely, variations in the quantity of potatoes lost in storage and in transit, owing principally to rot. In some years potatoes suffer seriously from rot in storage, especially from late blight rot, while in other years losses are very small. These losses have at least as much effect on price as a reduction in the quantity dug. Unfortunately, however, no accurate statistics have ever been kept on loss in storage, and it is not possible to predict the loss with any accuracy or even to know what it has been in any one year.

Since 1903 the Plant Disease Survey of the United States Department of Agriculture has kept records of reports on the prevalence of late blight in the fields. By going over these reports it is possible to make an estimate of whether late blight was light, moderate, or severe in any one year. Losses in storage from late blight rot are not exactly proportional to the extent of late blight in the fields, but it is interesting to compare the estimates of the extent of late blight with the fluctuations in the price of potatoes which remain after removing the effect of the five other factors considered. The dotted line in Figure 9 shows the variation in the extent of late blight in the fields. The data are so inadequate that no attempt was made to distinguish between years when the blight was "light" and those when it was "very light," or between years when it was "severe" and when it was "very severe." It is readily seen, however, that variations in loss in storage will explain a considerable proportion of the fluctuations in the price of potatoes which remain after removing the effects of the factors previously considered.

PRICE CHANGES DURING THE SEASON

Thus far we have considered only the changes from one year to the next in the average price for the season. It has been found possible not only to tell what are the factors which cause most of these changes, but also to measure the average effect of the five factors which explain most of the changes, namely, (1) value of the dollar; (2) an upward trend in the value of potatoes; (3) production in the late crop states; (4) the price of potatoes in August; and (5) variations in quality. It is not so easy to explain the changes in price during any one season. A general explanation of the causes of the changes can be given but no method has been found for determining what part of each change is due to each cause. Figure 13 shows the changes which actually occurred in the price of potatoes in St. Paul and Minneapolis from month to month for each season from September, 1899, to May, 1923. Figure 14 shows the changes from day to day during the 1923-24 season.

NORMAL SEASONAL CHANGE

One factor which we know must affect the price of potatoes during any one season is the fact that no one is willing to store potatoes from fall until spring unless he expects the price to rise enough to cover the costs of storage, including the inevitable shrinkage. Table XI shows the average price of potatoes for each month of the season for the 16 years from 1899 to 1915 and also the percentage relation of the price each month to the average price for the season. It is more convenient, however, to calculate seasonal variation in terms of cents rather than of percentages. The figures in the first column of Table XI cannot be used for this purpose under present conditions, as a greater change in prices from fall to spring must be expected than in the years before the war. Prices of potatoes and most costs of storage are higher now than in the years from which the averages shown in Table XI were calculated, and farmers and dealers require a greater increase in price from fall to spring to pay them to hold potatoes.

TABLE XI

SEASONAL VARIATION OF PRICE OF POTATOES IN MINNEAPOLIS AND ST. PAUL (SIXTEEN-YEAR AVERAGE, SEPTEMBER, 1899, TO MAY, 1915)

Month	Average price per cwt.	Per cent of average for season
	Cents	
September	82.3	96.2
October	75.8	88.6
November	78.5	91.7
December	79.8	93.2
January	85.8	100.3
February	91.3	106.6
March	92.6	108.3
April	95.1	111.1
May	94.0	109.9
Average (harmonic mean)	85.6	100.0

A good indication of the price changes to be expected during the average season at the present time is given in Table XII. The first column in Table XII shows the figures from the second column of Table XI expressed as percentages above and below the average for the season. The second column shows these percentages applied to a price of $1.28 per hundredweight, which is about normal for potatoes in St. Paul and Minneapolis with the general price level which has prevailed since 1920.

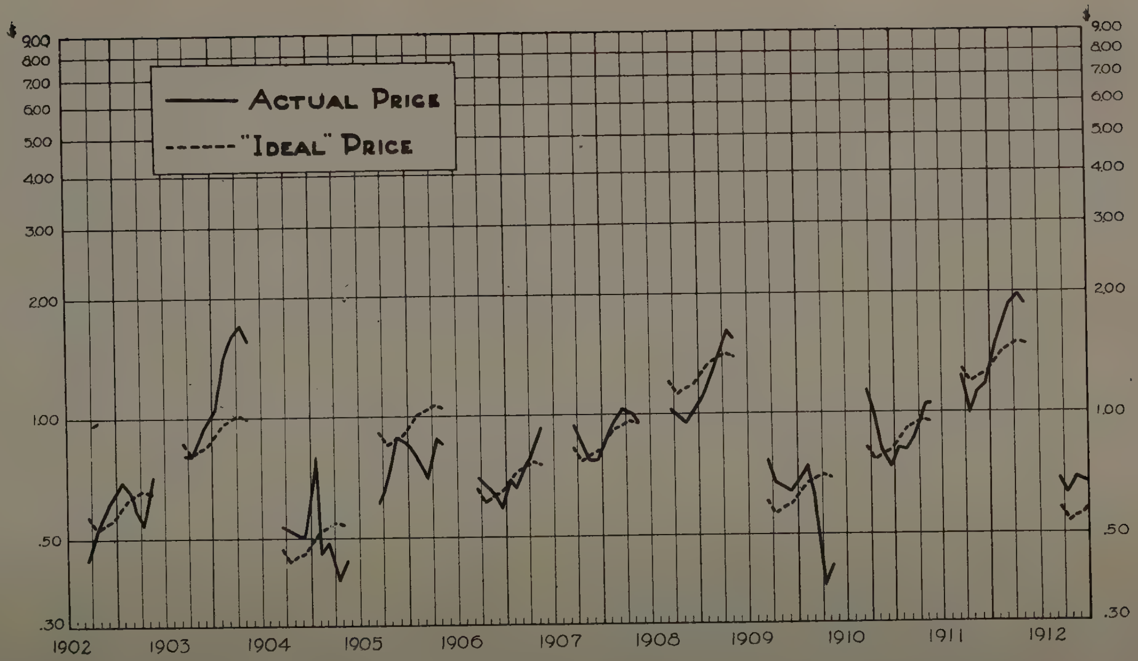
TABLE XII

SEASONAL VARIATION TO BE EXPECTED IN PRICE OF POTATOES ON PRESENT BASIS

Month	Percentage below or above average for season	Cents per cwt. below or above average for season*
		Cents
September	— 3.8	— 4.9
October	—11.4	—14.6
November	— 8.3	—10.6
December	— 6.8	— 8.7
January	+ 0.3	+ 0.4
February	+ 6.6	+ 8.4
March	+ 8.3	+10.6
April	+11.1	+14.2
May	+ 9.9	+12.7

* Based on average price of $1.28.

From this table it is easy to calculate the increase in price to be expected between any two months. For example, comparing October and April we expect a price in October 14.6 cents below the average for the season and a price in April 14.2 cents above the average for the season, which means that we expect an increase in price from October to April amounting to 28.8 cents per hundredweight. Every farmer should figure out for himself whether he can make money storing potatoes for this increase in price.


$
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.50
.30
ACTUAL PRICE
"IDEAL" PRICE
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912

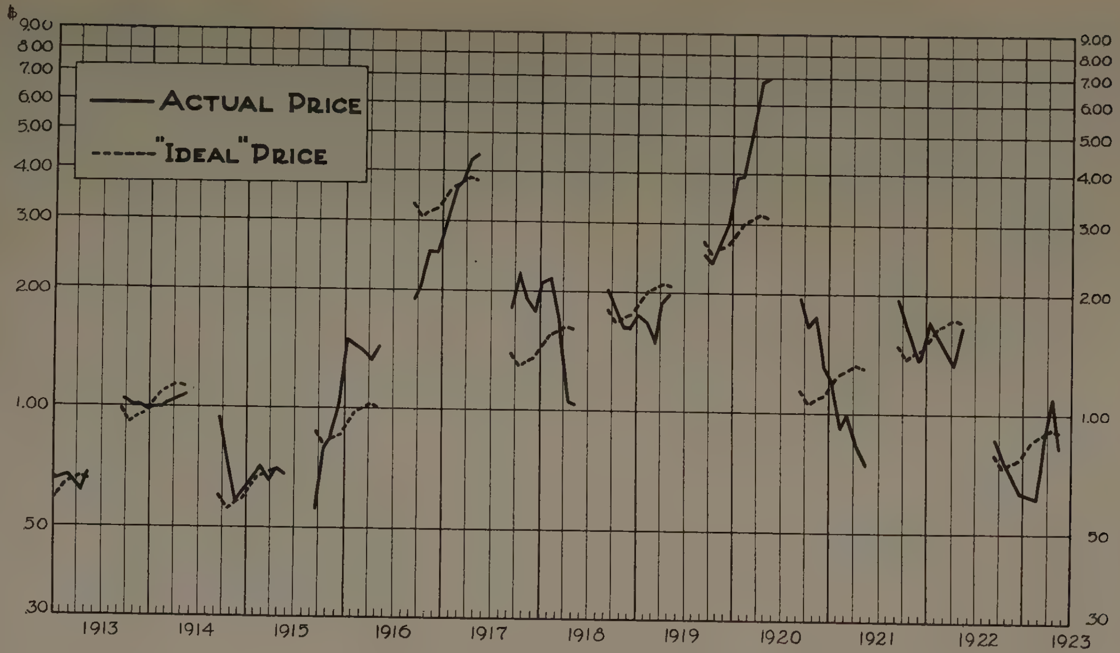


Fig. 13. Actual and "Ideal" Price of Potatoes Monthly, 1902-23

The "ideal" price shown is the price which would have prevailed if the percentage changes from month to month had always been the same as in the average year and if the average price for the season had been that justified by the first four factors considered in this bulletin. Frequently the price starts too low in the fall and rises sharply before spring or else starts too high in the fall and has to be lowered before spring in order to move the crop.

A glance at Figure 13 will show that it is very unusual for the price during any one year to show the normal or average seasonal change. The dotted lines marked "ideal" price show how the price would have varied each year if the average for the season had been affected only by the first four of the five factors affecting the seasonal average price which we considered above, and if the price had changed during the season so as to give the average percentage change from month to month. Perhaps "ideal" is not the best term to apply to a price which would change in this way; anyone who wishes may call it by a different name. The purpose is to show what the price would have been each month if it had been affected only by the value of the dollar, the trend of value, the price in August, and the normal change from month to month.

OTHER REASONS FOR CHANGES FROM MONTH TO MONTH

Of course the principal reason that the price of potatoes changes so much from month to month, and even from day to day, sometimes upward, sometimes downward, is that no one ever knows just what the price ought to be. For example, in 1923-24 the price started fairly high in September, as may be seen from Figure 14. The crop of early potatoes was short and the price was high throughout the summer. The late crop was about normal and most people recognized that the price could not stay as high as it was in September. Farmers wanted to sell at September prices and dealers hesitated to buy, hence the price fell. As it went lower, more farmers felt inclined to hold their potatoes or more dealers were willing to buy potatoes for storage, or both, and finally the price stopped falling. As a matter of fact, farmers and dealers, between them, had allowed the price to go too low, and late in December it was discovered that, at the prices then existing, there probably would not be enough potatoes to go around. The result was a sudden jump in the price from 80-85 cents a hundredweight on December 26 to $1.25-$1.30 on January 8. But many farmers and dealers thought this price too high and it was gradually forced down a few cents a week. Late in May it was discovered that the supply of old potatoes was running short and the price rose again, going from $1.10 a hundredweight on May 24 to $1.40 to $1.45 on the last of May and still higher during June.

Clearly the principal cause of these changes during the season is to be found in the mistakes farmers and dealers make in guessing what the price ought to be. In fact, it has been found possible to predict these mistakes of judgment pretty accurately. When the production is very large, farmers and dealers are usually too optimistic in the fall; they do not appreciate how low the price will have to go to sell all the crop. As a result the price stays too high in the fall and later has to be lowered to move the crop. Similarly, when the crop is unusually short, farmers and dealers seldom realize how high a price can be got for what potatoes there are, and the price starts too low in the fall and rises before spring. Farmers' Bulletin No. 1317, (p. 6) of the United States Department of Agriculture, entitled "Marketing Main-Crop Potatoes," gives the following summary:

> As a rule, whenever production has approached or exceeded 4 bushels per capita, the price has tended downward, but the price trend has been upward whenever the average yield fell below 3.2 bushels per capita.
>
> During the last twenty years, the grower was apparently justified in holding only when the indicated crop was far below the average, or not much over 3 bushels per capita. In other years, the chance of profit to the grower was too uncertain to balance the added risk, cost, and shrinkage.

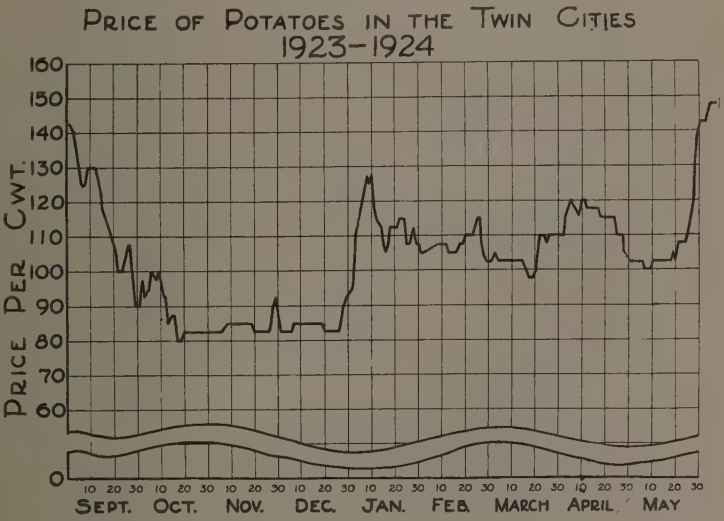


Fig. 14. Daily Changes in Price of Potatoes During 1923-24

The crop of early potatoes was short in 1923 and prices were high. When the late crop came on, prices fell sharply to a range of 80 to 85 cents. In the last days of December, fear of a shortage of potatoes caused the price to rise again. The market remained uncertain throughout the rest of the year, finally rising sharply because of a shortage at the end of the season.

Of course, if most farmers followed this rule and held their potatoes until spring in years of short crops, the rule would cease to work; their holding in the fall would force the price up in the fall and when they began to sell it would drop again.

TABLE XIII

RELATION OF PRICES TO OWNERSHIP OF STOCKS OF POTATOES ON JANUARY 1, 1916-24*

Year	Production per capita in 27 late crop states	Price per cwt. in St. Paul and Minneapolis		Stocks on hand January 1		Proportion of stock January 1 held by			
						Dealers		Growers	
		Fall†	Spring‡	Nineteen surplus late crop states	Minnesota	Nineteen states	Minnesota	Nineteen states	Minnesota
	Bu.			Per cent of crop	Per cent of crop	Per cent	Per cent	Per cent	Per cent
1915-16..........	2.77	$0.90	$1.38	32.6	29.9	17.6	28	82.4	72
1916-17..........	2.14	2.34	4.22	26.1	24.0	26.3	38	73.7	62
1917-18..........	3.10	2.02	1.28	32.2	32.5	14.6	20	85.4	80
1918-19..........	2.89	1.68	1.81	29.9	27.3	16.2	24	83.8	76
1919-20..........	2.62	2.71	6.48	26.0	21.5	20.6	24	79.4	76
1920-21..........	3.20	1.57	0.86	35.3	32.5	14.8	20	85.2	80
1921-22..........	2.81	1.52	1.47	31.4	30.1	20.0	27	80.0	73
1922-23..........	3.46	0.70	0.93	36.3	41.1	14.2	26	85.8	74
1923-24..........	3.08	0.85	1.09	33.8	33.0	13.3	24	86.7	76

* Figures from U.S.D.A. Yearbook, 1922, pp. 673-74; and 1923, pp. 765-66.

† October, November, and December.

‡ March, April, and May.

Another thing worth noticing about these mistakes in guessing what the price ought to be is that on the average dealers guess a little better than farmers. Table XIII shows that averaging the 6 years in which prices have risen between fall and spring, Minnesota dealers held 27 per cent of the stocks on January 1, while in the 3 years in which prices fell, dealers held only 22 per cent of the total stocks on January 1. Apparently, dealers generally use somewhat better judgment than farmers in deciding when to hold potatoes and when not.

CARLOT SHIPMENTS OF POTATOES

Many farmers and dealers consider it worth while to keep track of carlot shipments of potatoes. Table XIV shows the number of cars shipped from Minnesota and certain other important states, and from all states during each month since the figures have been collected, also the percentage of the total United States shipments each month to the total for the season.

Table XV shows the estimated production for the states included in Table XIV for each year since 1917, and the percentage of the crop entering into carlot shipments. The percentages for 1917-18 appear small and probably indicate that the figures were less complete during the first year. No figures are collected on shipments by wagon and truck direct to cities where the potatoes are consumed. In both Table XIV and Table XV, space is left for filling in figures for future years.

CALCULATING EFFECTS OF FACTORS THAT INFLUENCE PRICE

In connection with the foregoing discussion of each factor influencing the price of potatoes, figures have been given which will enable any one to calculate the effect of that factor in each year from 1925 to 1927. The effects may be calculated more simply, however, from the following formulas, which are merely short-cut methods of doing the figuring already described.

For the benefit of those who find it difficult to get the latest estimates of production in the 27 late crop states, the Bureau of Labor Statistics index number, and other statistics on the current situation, the Minnesota Agricultural Experiment Station issues a potato market letter each month from September to January and at appropriate times during the remainder of the season. This letter contains the latest figures on the price situation and a discussion of the way in which each factor is likely to affect the price of potatoes. It may be obtained regularly by applying to the Division of Publications, University Farm, St Paul.

TABLE XIV

MONTHLY AND YEARLY CAR LOT SHIPMENTS OF POTATOES, 1917-18 TO 1923-24*

State and year	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Total
	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars
Minnesota																	
1917-18	....	....	....	15	1,312	1,918	4,074	1,445	675	1,261	1,510	2,119	1,328	625	179	16	16,477
1918-19	....	....	....	96	3,099	4,573	4,623	1,733	758	1,839	1,359	2,365	1,612	1,018	434	6	23,515
1919-20	....	....	....	83	2,438	5,359	5,817	1,324	693	1,875	1,162	1,900	1,027	262	117	1	22,058
1920-21	....	....	....	64	1,344	2,770	6,870	3,279	934	1,469	1,723	2,542	1,133	863	214	9	23,214
1921-22	....	....	....	....	960	4,869	9,029	2,197	892	1,894	1,442	4,443	2,514	1,080	248	....	29,568
1922-23	....	....	....	508	1,432	4,167	7,062	2,466	659	1,724	1,532	4,215	3,274	1,390	481	21	28,931
1923-24	....	....	....	15	1,755	6,157	7,904	2,712	1,095	2,560	3,845	3,815	2,426	1,008	289	3	33,584
1924-25																	
1925-26																	
1926-27																	
Wisconsin																	
1917-18	....	....	....	....	118	1,158	3,707	1,383	575	887	1,461	1,643	1,452	1,011	447	10	13,852
1918-19	....	....	....	1	134	2,768	4,630	2,464	1,545	2,460	1,598	2,122	1,608	963	362	....	20,655
1919-20	....	....	....	....	127	3,250	7,019	2,810	1,567	2,137	1,754	1,923	893	344	148	3	21,975
1920-21	....	....	....	....	18	450	3,189	2,876	1,214	2,337	1,933	2,385	2,234	1,592	431	2	18,661
1921-22	....	....	....	....	76	754	2,125	719	626	1,367	1,201	1,993	1,166	755	260	3	11,045
1922-23	....	....	....	....	205	1,377	3,685	2,018	1,635	2,495	1,906	2,992	2,716	1,735	944	58	21,766
1923-24	....	....	....	....	189	1,294	2,629	1,476	1,102	1,954	2,260	2,009	1,860	1,678	609	8	17,008
1924-25																	
1925-26																	
1926-27																	

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* U. S. D. A. Yearbook, 1924, pp. 713, 714, 715, and 716.

TABLE XIV—*Continued*

MONTHLY AND YEARLY CAR LOT SHIPMENTS OF POTATOES, 1917-18 TO 1923-24*

State and year	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Total
	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars
Michigan																	
1917-18	....	....	....	....	16	388	1,572	1,296	598	458	751	938	1,326	1,553	531	4	9,431
1918-19	....	....	....	....	20	328	1,547	2,072	743	790	592	1,154	1,725	1,291	770	30	11,062
1919-20	....	....	....	....	50	601	2,687	2,329	1,043	1,099	1,011	1,714	1,134	543	26	....	12,237
1920-21	....	....	....	2	39	577	2,210	3,116	1,253	1,630	990	1,657	2,174	2,632	813	26	17,119
1921-22	....	....	....	....	3	789	3,210	1,886	880	1,516	1,240	2,041	1,522	1,414	718	3	15,222
1922-23	....	....	....	....	76	1,216	2,600	2,477	1,380	1,474	1,419	2,170	2,924	2,321	1,630	149†	†19,836
1923-24	....	....	....	....	46	878	2,490	2,587	1,292	1,823	2,201	2,567	2,880	2,599	1,032	10	20,405
1924-25																	
1925-26																	
1926-27																	
New York																	
1917-18	....	....	....	36	733	1,052	2,228	1,043	478	913	1,145	1,104	891	413	74	....	10,110
1918-19	....	....	....	80	608	1,169	2,067	1,265	875	902	687	1,012	927	374	116	7	10,089
1919-20	....	....	....	117	782	516	2,920	2,071	982	1,298	1,153	1,929	817	214	15	3	12,817
1920-21	....	....	....	53	336	999	2,363	2,636	1,008	1,316	1,787	2,317	2,063	1,429	192	3	16,502
1921-22	....	....	....	203	1,360	2,121	4,914	1,946	1,356	2,138	1,517	1,818	1,129	428	57	1	18,988
1922-23	....	.....	....	93	815	1,770	3,396	2,662	1,830	2,207	2,058	2,851	1,159	354	91	3	19,291
1923-24	....	....	6	65	1,866	1,716	2,346	1,903	1,070	1,771	1,839	2,321	2,143	1,396	183	....	18,625
1924-25																	
1925-26																	
1926-27																	

† Includes 8 cars in August.

TABLE XIV—*Continued*

MONTHLY AND YEARLY CAR LOT SHIPMENTS OF POTATOES, 1917-18 TO 1923-24*

State and year	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Total
	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars
Maine																	
1917-18	....	....	....	....	71	1,699	1,986	1,331	1,390	1,808	1,673	2,020	1,530	825	445	16	14,794
1918-19	....	....	....	....	91	2,076	2,466	1,596	1,700	1,979	1,417	2,471	2,281	1,618	1271	60	19,026
1919-20	....	....	....	....	947	2,211	3,338	2,543	2,465	2,837	1,474	2,796	3,493	1,208	132	....	23,444
1920-21	....	....	....	....	91	1,126	2,170	2,046	1,478	2,478	2,036	2,495	1,778	1,643	458	18	17,817
1921-22	....	....	....	....	579	4,452	4,681	2,882	2,768	3,569	3,386	4,473	4,814	4,459	1918	56	38,037
1922-23	....	....	....	....	198	1,778	3,077	2,675	2,359	2,717	2,782	3,513	2,589	1,533	1,137	43	24,401
1923-24	....	....	....	....	293	3,959	5,780	3,645	3,025	4,321	3,876	4,100	3,128	2,065	528	1	34,721
1924-25																	
1925-26																	
1926-27																	
New Jersey																	
1917-18	....	....	....	112	4,669	3,919	1,979	563	76	57	84	105	111	27	7	....	11,709
1918-19	....	....	2	303	3,075	1,641	368	223	110	27	32	48	41	13	6	....	5,889
1919-20	....	....	....	618	4,971	3,292	970	410	56	32	2	50	3	5	....	....	10,409
1920-21	....	....	....	1,567	5,242	6,282	2,747	969	118	37	24	109	37	15	....	....	17,147
1921-22	....	....	....	2,107	5,854	1,634	377	284	49	23	55	75	16	2	....	....	10,476
1922-23	....	....	7	2,234	8,387	4,756	1,971	609	73	34	9	174	72	9	....	....	18,335
1923-24	....	....	....	86	3,869	1,706	343	184	15	13	18	90	21	7	....	....	6,352
1924-25																	
1925-26																	
1926-27																	

TABLE XIV—*Concluded*

MONTHLY AND YEARLY CAR LOT SHIPMENTS OF POTATOES, 1917-18 TO 1923-24*

Year	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Total
Total U. S.	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars	Cars
1917-18	1483‡	6835	13,923	15,478	12,910	14,292	23,542	13,536	7,120	9,555	11,009	12,619	10,212	6,714	2287	81	161,596
1918-19	1321§	6006	14,702	14,075	11,805	19,841	24,902	15,442	8,891	12,753	8,998	13,739	12,653	7,657	3596	171	176,552
1919-20	781§	2226	9,707	13,684	13,626	22,257	32,535	17,362	9,532	12,883	8,725	12,771	8,359	2,922	492	8	167,870
1920-21	87‡	4038	14,285	15,614	13,592	18,155	31,522	25,075	9,755	14,106	11,970	16,039	12,957	9,561	2347	62	199,165
1921-22	2051‖	5426	15,298	16,979	16,115	26,040	43,250	16,729	10,496	16,705	13,717	22,109	17,489	11,910	4161	71	238,546
1922-23	2780¶	8304	17,869	18,758	18,238	24,420	35,188	21,047	12,447	17,261	14,606	24,416	22,043	10,989	5.520	291††	254,177
1923-24	1183**	5311	14,774	16,450	16,727	24.044	35,220	20,732	11,977	19,739	20,688	22,816	17,780	11,110	3,171	25	241,747
1924-25																	
1925-26																	
1926-27																	
Total season for U. S.	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1917-18	0.9	4.3	8.7	9.6	7.4	8.9	14.6	8.4	4.4	6.0	6.9	7.8	6.4	4.2	1.4	0.1	100.0
1918-19	0.7	3.4	8.3	8.0	6.7	11.2	14.1	8.8	5.0	7.2	5.1	7.8	7.2	4.3	2.1	0.1	100.0
1919-20	0.5	1.3	5.8	8.1	8.1	13.3	19.4	10.3	5.7	7.7	5.2	7.6	5.0	1.7	0.3	0.0	100.0
1920-21	0.1	2.0	7.2	7.8	6.8	9.1	15.8	12.6	4.9	7.1	6.0	8.1	6.5	4.8	1.2	0.0	100.0
1921-22	0.8	2.3	6.4	7.1	6.8	10.9	18.3	7.0	4.4	7.0	5.7	9.2	7.4	5.0	1.7	0.0	100.0
1922-23	1.1	3.3	7.0	7.4	7.2	9.6	13.8	8.3	4.9	6.8	5.7	9.6	8.7	4.3	2.2	0.1	100.0
1923-24	0.5	2.2	6.1	6.8	6.9	9.9	14.6	8.6	5.0	8.2	8.6	9.4	7.3	4.6	1.3	0.0	100.0
1924-25																	
1925-26																	
1926-27																	

‡ Includes 1 car in March.
§ Includes 5 cars in March.
‖ Includes 115 cars in March.
¶ Includes 1 car in February and 221 cars in March.
** Includes 36 cars in March.
†† Includes 8 cars in August.

TABLE XV

ESTIMATED QUANTITIES OF POTATOES SHIPPED IN CAR LOTS AND PERCENTAGES OF TOTAL CROP FOR CERTAIN STATES, 1917-18 TO 1923-24

	1917-18	1918-19	1919-20	1920-21	1921-22	1922-23	1923-24	1924-25	1925-26
				Thousand Bushels					
ESTIMATED NUMBER OF BUSHELS IN CARLOT SHIPMENTS:									
Minnesota	9,886	14,109	13,235	13,928	17,741	17,345	19,999	.....	.....
Wisconsin	8,311	12,393	13,185	11,197	6,627	13,058	9,341	.....	.....
Michigan	5,659	6,637	7,342	10,271	9,133	11,897	10,586	.....	.....
New York	6,066	6,053	7,690	9,901	11,393	11,577	10,866	.....	.....
Maine	8,876	11,416	14,066	10,690	22,822	14,631	20,746	.....	.....
New Jersey	7,025	3,533	6,245	10,288	6,286	11,001	3,818	.....	.....
Total United States	96,958	105,931	100,722	119,499	143,128	203,302	140,664	.....	.....
				Thousand Bushels					
ESTIMATED PRODUCTION:									
Minnesota	33,600	32,760	28,844	31,581	32,200	43,740	40,698	.....	.....
Wisconsin	34,998	33,040	28,388	33,264	21,400	40,672	26,112	.....	.....
Michigan	35,910	28,560	27,000	36,225	27,200	37,842	35,796	.....	.....
New York	38,000	34,960	33,790	40,625	34,000	37,400	39,729	.....	.....
Maine	20,250	22,400	25,530	21,771	38,400	25,245	31,992	.....	.....
New Jersey	11,172	8,464	7,968	14,040	9,000	16,435	7,790	.....	.....
Total United States	442,108	411,860	322,867	403,296	361,659	453,396	416,105	.....	.....
PERCENTAGE OF PRODUCTION IN CARLOT SHIPMENTS:	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
Minnesota	29.4	43.1	45.9	44.1	55.1	39.7	49.1	....	....
Wisconsin	23.8	37.5	46.4	33.7	31.0	32.1	35.8	....	....
Michigan	15.8	23.2	27.2	28.4	33.6	31.4	29.6	....	....
New York	16.0	17.3	22.8	24.4	33.5	31.0	28.8	....	....
Maine	43.8	51.0	55.1	49.1	59.4	58.0	64.8	....	....
New Jersey	62.9	41.7	78.4	73.3	69.8	67.0	49.0	....	....
Total United States	21.9	25.7	31.2	29.6	39.6	44.8	33.8	....	....

CONVENIENT TABLES AND FORMULAS

A. TO CALCULATE THE EFFECT OF (1) VALUE OF THE DOLLAR; (2) TREND OF VALUE; (3) PRODUCTION IN LATE CROP STATES; AND (4) PRICE IN AUGUST

The price which would result if these four factors only affected it, is given by the following formulas. The formula must be changed slightly for each year to allow for changes in the normal value of potatoes, the normal production, and the normal value in August in New York City. The price obtained applies to the U. S. No. 1 round whites in St. Paul and Minneapolis.

1923

$$\text{Price per cwt. (dollars)} = \frac{L}{.733\,C + .58\,\frac{L_A}{P_A} - 159}$$

1924

$$\text{Price per cwt. (dollars)} = \frac{L}{.725\,C + .58\,\frac{L_A}{P_A} - 159}$$

1925

$$\text{Price per cwt. (dollars)} = \frac{L}{.717\,C + .57\,\frac{L_A}{P_A} - 159}$$

1926

$$\text{Price per cwt. (dollars)} = \frac{L}{.710\,C + .57\,\frac{L_A}{P_A} - 159}$$

1927

$$\text{Price per cwt. (dollars)} = \frac{L}{.703\,C + .57\,\frac{L_A}{P_A} - 159}$$

The proper figures must be substituted for the letters in the formulas as follows:

L=estimated price level for the season, based on the Bureau of Labor Statistics "All Commodities" index number

C=estimated crop in 27 late crop states (as listed in Table III) expressed in millions of bushels

L_A=price level in August, as shown by the Bureau of Labor Statistics index number

P_A=average price of New Jersey Giants and Cobblers in New York City during August, dollars per 150-pound sack.

The use of this formula may be illustrated with the figures for 1923. The figures to be used in the formula for 1923 are as follows:

$L=151$ per cent of 1913
$C=343.9$* million bushels
$L_A=150$ per cent of 1913
$P_A=3.64$ dollars per 150-pound sack.

Applying these figures in the formula for 1923 we get:

$$\text{Price per cwt.} = \frac{151}{.733 \times (343.9) + .58 \left\{ \dfrac{150}{3.64} \right\} - 159}$$

Making the necessary calculations one step at a time, this gives:

$$\text{Price per cwt.} = \frac{151}{252 + 24 - 159} = \frac{151}{117} = \$1.29$$

B. TO CALCULATE THE EFFECT OF VARIATIONS IN QUALITY

As noted on p. 18 the quality of Minnesota potatoes is quite reliably indicated by a comparison of prices in St. Paul and Minneapolis and prices of Maine and New York State potatoes in New York City, provided the other factors affecting the difference are considered also. To make this comparison, it is necessary to have the following data, represented by the letters as indicated:

L†—Estimated price level for the season, based on the Bureau of Labor Statistics index number of wholesale prices of "all commodities."
C†—Estimated crop in 27 late crop states, expressed in millions of bushels.
C_W—Estimated crop in 7 western states,‡ expressed in millions of bushels.
F—Mean of freight rates per hundred pounds on potatoes from St. Paul or Minneapolis to Cincinnati and to Pittsburgh.
D—Difference between the price per hundredweight of Minnesota round whites in St. Paul and Minneapolis and the average of prices of Maine Green Mountains and New York round whites in New York City.

These figures are then to be substituted in one of the following formulas, the formulas for different years being slightly different.

---

* This estimate of the 1923 production was revised in December, 1924, but is used in the illustration because it was the best figure available in 1923.

† These are the same figures already used.

‡ North Dakota, South Dakota, Minnesota, Wisconsin, Iowa, Nebraska, and Illinois.

1923

$$\text{Correction for quality (cents)} = L(.00083\,C - .152) + F\left(7.47\,\frac{C_W}{C} - 1.64\right) - .98\,D$$

1924

$$\text{Correction for quality (cents)} = L(.00082\,C - .149) + F\left(7.47\,\frac{C_W}{C} - 1.65\right) - .98\,D$$

1925

$$\text{Correction for quality (cents)} = L(.00081\,C - .145) + F\left(7.47\,\frac{C_W}{C} - 1.67\right) - .98\,D$$

1926

$$\text{Correction for quality (cents)} = L(.00080\,C - .142) + F\left(7.47\,\frac{C_W}{C} - 1.68\right) - .98\,D$$

1927

$$\text{Correction for quality (cents)} = L(.00080\,C - .139) + F\left(7.47\,\frac{C_W}{C} - 1.70\right) - .98\,D$$

The use of the formula may be illustrated with figures for 1923, a year in which it was especially important to correct for quality. For 1923 we have the following values:

$L = 151$ per cent of 1913
$C = 343.9$ million bushels
$C_W = 110.5$ million bushels
$F = 44.5$ cents per cwt.
$D = 95$ cents per cwt.

Substituting these figures in the formula for 1923 gives the following:

$$\begin{aligned}\text{Correction for quality} &= 151(.00083 \times 343.9 - .152) + 44.5\left(7.47\,\frac{110.5}{343.9} - 1.64\right) - .98 \times 95\\ &= 151(.285 - .152) + 44.5(2.40 - 1.64) - .98 \times 95\\ &= 151(.133) + 44.5(.76) - .98 \times 95\\ &= 20.1 + 33.8 - 93.1\\ &= -39.2 \text{ cents per cwt.}\end{aligned}$$

Note that in this case the correction for quality is to be subtracted, as it is a minus quantity. The quality of Minnesota round whites was unusually poor in 1923. In some years the quality is unusually good and the correction for quality is a plus and is added to the price calculated from the four other factors included in the first formula. The final figure for 1923 is therefore:

Calculated price based on 4 factors	$1.29 per cwt.
Correction for quality	—.39
Calculated price based on 5 factors	$ .90 per cwt.

The actual average price for 1923, as shown in Table I, was $1 per hundredweight. The quality of Minnesota potatoes in 1923 was really not so poor as the market rated it in November. Later in the season prices of Minnesota round whites improved as compared with other potatoes.

C. TO CALCULATE THE PRICE JUSTIFIED BY THE FIVE FACTORS IN ANY ONE MONTH

The formulas given above apply to the average price for the nine months from September to May for U.S. No. 1 round whites in St. Paul and Minneapolis. To calculate the price which these factors justify for any one month, it is necessary to subtract or add a certain amount to allow also for the normal seasonal variation.

NORMAL SEASONAL VARIATION IN THE PRICE OF POTATOES

Month	Deviation from average price for season* Cents per cwt.
September	— 4.9
October	—14.6
November	—10.6
December	— 8.7
January	+ 0.4
February	+ 8.4
March	+10.6
April	+14.2
May	+12.7

* Calculated on the assumption of a normal price of potatoes of $1.28 per cwt.

TECHNICAL BULLETIN 30 SEPTEMBER 1925

University of Minnesota
Agricultural Experiment Station

Control of Soil Heterogeneity and Use of the Probable Error Concept in Plant Breeding Studies

H. K. Hayes
Division of Agronomy and Farm Management

UNIVERSITY FARM, ST. PAUL

AGRICULTURAL EXPERIMENT STATION

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CONTROL OF SOIL HETEROGENEITY AND USE OF THE PROBABLE ERROR CONCEPT IN PLANT BREEDING STUDIES

By H. K. Hayes

The importance of plant breeding has become more generally recognized in recent years. This to some extent, probably is a result of a growing appreciation of the need of obtaining varieties resistant to fungus and insect parasites. The problem of a determination of the comparative value of numerous new productions has become greatly complicated, however, by the increasing number of new varieties which must be compared.

The Mendelian mode of attack in the synthesis of new varieties necessitates the study of large numbers of new strains. The realization that most, if not all, important economic characters are the result of the interaction of many factors plus environment is, perhaps, the main reason from a genetic standpoint why large numbers should be used.

For these reasons the question of better methods for trying out new varieties has received considerable study altho at present investigators differ as to methods. In breeding self-fertilized crops, such as most small grains, a uniformity of procedure for comparative trial of large numbers of new strains has been evolved. The plan developed in the United States for the preliminary trial of numerous strains of small grains is known as the rod-row method. There is some variation in details such as the use of single- or three-row plots; the rate of seeding for varieties which differ in grain size; the number of replications; and the method of sowing the grain. Further study will make it possible eventually to standardize these procedures; it is not feasible, however, to carry on the studies in all localities in the same manner as environmental conditions, the number of strains under comparison, and other factors greatly influence the accuracy and value of the methods.

The subject uppermost in the minds of many field plot technicians at the present time may be stated in the form of a question,—what is the best means of comparing and eliminating varieties after all possible care has been taken to conduct the study in a desirable manner with the facilities available? This has led to a critical study of the use of probable errors in the elimination of new varieties.

It seems unnecessary in the present paper to review the literature in this field as this has been discussed in various papers.[1] The different uses of the probable error concept being studied can be grouped under three general heads: (1) the calculation of probable errors for each separate strain in the test; (2) the use of "Student's method" of comparing varieties; and (3) the calculation of a probable error of the experiment by the use of check plots or some method whereby the results from all varieties can be used for the calculation of a single probable error for the experiment.

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[1] See Journal American Society of Agronomy, Vol. 15, and various reports of the Varietal Standardization Committee in the same journal.

A detailed comparison of the three methods would be of interest. At present, however, it seems desirable to point out briefly some of the difficulties and desirable points in each altho (3), the calculation of a single probable error of the experiment will be discussed in some detail.

With a single variety harvested in one-fortieth acre plots and under rather carefully conducted experimental conditions it was learned that when the yields of four systematically replicated plots were used for each calculation that with a total of 50 comparisons there were two probable error calculations which differed from each other to such an extent that one was over 900 per cent larger than the other [Kiesselbach (7), Hayes (5)]. This result, which on purely mathematical bases, might be expected somewhat frequently seems a sufficient reason to doubt the wisdom of using in the comparison of two varieties probable error calculations based on as few as 3 or 4 plots. This opinion is at some variance with a recent one as stated by Love (10) who certainly deserves much credit for stimulating a more general interest in the subject. Love says, "In answer to the criticism of some that the probable error concept cannot be applied to a small number of observations, it is well to add that if this is so we should place little dependence on a mean or other constant obtained from a few observations" and also "yet when necessary it is better to calculate it," that is, a probable error, "from two or three plots rather than not use it at all." Perhaps there is little difference of opinion after all between Love and the writer for it is hardly ever necessary to calculate a probable error from few comparisons. If the probable error itself is no more accurate than the mean it is scarcely conceivable that it is of great value as an aid in comparing two means.

The method developed by "Student" (15, 16) for comparing two series of results was first brought to the attention of American investigators by Love (8). In its application to varietal trials this method involves pairing like plots and the use of student tables for small numbers of replications. In this discussion the term "Students Method" refers to the pairing of results. The same philosophy would apply to the standard deviation of successive differences used with the ordinary tables of probabilities. In varietal or strain comparisons "Student's Method" is applicable for those cases where paired comparisons are available and while under certain conditions its use greatly facilitates the study, it is perhaps not as valuable for the plant breeder as for other investigators. It may be desirable to point out some limitations in its use for the plant breeder.

In a comparison of two wheat varieties, one of which is resistant to stem rust and the other susceptible, let us suppose that both have approximately the same yielding ability when rust is not a factor and in addition let us suppose that one is resistant and the other susceptible under rust epidemic conditions. In a five-year test we may further suppose that the yield of the susceptible variety is reduced 50 per cent by rust one year when rust was a major factor. All data are hypothetical in this problem but there is no reason for believing that such a case might not occur.

The hypothetical comparison is outlined here:

Year	Variety 1	Variety 2	D	D′	D′²
1	40	42	—2	6	36
2	42	40	2	2	4
3	40	42	—2	6	36
4	42	40	2	2	4
5	40	20	20	16	256
			5|20		5|336
			4		67.20
$Z=\frac{4}{8.2}=4.9$					$S.D.=\sqrt{67.20}=8.2$

The chances are 4.24:1 that the difference is significant (9). A separate probable error calculated each year would have led without doubt to the conclusion that the varieties were significantly different in yielding ability one year out of five.

To be strictly accurate in field plot trials where there is correlation in the yielding ability of nearby plots Student's method should be used only for paired comparisons. In variety trials conducted for several years the yearly averages represent seasonal pairs but do not adequately take into account soil heterogeneity. Two writers have pointed out in the field of agronomy [Kemp (6), Richey (11)] that the probable error of a difference should consider the correlation between the two series of comparable variables. If there is a correlation in the yielding ability of nearby plots this leads to a reduction in the probable error of a difference and a perfect correlation or 1 reduces the probable error of a difference to approximately 0. In plant breeding studies, however, where small plots are used the use of the correlation coefficient is perhaps not as necessary as in some other kind of field studies. This is to some extent due to the fact that over a three-year period two varieties will not be grown in the same relationship to each other.

Some plant breeders, likewise, change the order of the series thus partially overcoming the error which arises from neglecting the correlation coefficient in computing the probable error of a difference.

The computation of a single probable error in percentage, representing the error which arises from soil heterogeneity and other uncontrollable errors, is a convenient method for the plant breeder. The present paper is largely a consideration of the method of computing probable errors by what is called the "Deviation from the Mean Method" used for several years by the writer. It is similar in nature to the pairing method outlined by Wood and Stratton (17) in that it allows all plots of all varieties in the test to be used in computing the probable error of the experiment, i.e., the probable error which represents soil heterogeneity and other errors of a non-systematic nature.

After presenting the method of calculation and the use of the probable error obtained, results will be given which indicate the extent of error in rod-row trials resulting from the failure to use the correlation coefficient in obtaining the probable error of a difference.

THE DEVIATION FROM THE MEAN METHOD OF CALCULATING A PROBABLE ERROR

A plant breeder, in the majority of cases, centers his attention chiefly upon a few characters at a time and discards rather freely. For this reason the strains which are under trial are perhaps not widely different in general adaptability. For several years in the Minnesota plant breeding studies a comparison of probable errors as calculated by different methods has been made.

Check plots of standard varieties—Marquis wheat, Manchuria (Minn. No. 184) barley, and Victory oats—have been planted every fifth to tenth plot throughout the rod-row trials and probable errors calculated from these plots[2] have been used as standards for comparison of other methods of obtaining probable errors. In a previous paper [Hayes, (5)] probable errors obtained by the deviation from the mean method and Wood and Stratton's pairing method were compared with the probable errors as obtained from the use of check plots. It was found that the deviation from the mean method gave results which were closer to those obtained from check plots than were the probable errors calculated from the pairing method. Garber and others (2), at West Virginia, have compared probable errors computed from check plots with those obtained from the deviation from the mean method for a three-year period for buckwheat and for two years for oats and wheat. Agreements were good except for buckwheat, in 1921, when the deviation from the mean method gave a probable error twice as

[2] The formula used was $\text{P.E.} = \pm .6745 \sqrt{\frac{\Sigma(d^2)}{n}}$

great as by the use of check plots. The only other wide variation was in 1923 for wheat studies, the percentage probable error by the check plot method being 12.9 and by the deviation from the mean method, 18.9.

The computation method where the yields obtained from different varieties are used to calculate a single probable error in percentage may be given as follows:

COMPUTING OF PROBABLE ERRORS BY THE DEVIATION FROM THE MEAN METHOD

1. Express in per cent the deviation of each plot of each variety from its variety mean.
2. Square these percentage deviations and sum by adding all squared deviations.
3. Divide the sum of the squared deviations by the total number of deviations and extract the square root.
4. After extracting the square root multiply the value obtained by ±.6745. The value obtained is the probable error of a single plot test in percentage.
5. To compute the probable error of any number of systematically distributed plots, (n) divide the P.E. of a single plot by the $\sqrt{n}$.
6. Multiply the yield by the percentage probable error to obtain a probable error in bushels.

The method of computation may be illustrated altho much larger numbers are desirable than are used in the illustration. One of the advantages of the plan is that so many deviations are obtained that an accurate estimate of the extent of variability is reached. The plan is illustrated for two varieties each grown in four systematically distributed plots. Commonly, at least 100 deviations are available in plant breeding studies.

Illustration of Method

Variety	Yield each plot in bu.	Mean	Dev. in bu.	Dev. in per cent	Dev. in per cent squared
Marquis x Iumillo	35.4		4.6	11.50	132.25
II-15-44	48.0	40.0	8.0	20.00	400.00
	37.3		2.7	6.75	45.56
	39.2		0.8	2.00	4.00
Marquis x Kanred	35.5		2.7	7.07	49.98
II-15-58	44.4	38.2	6.2	16.23	263.41
	37.4		0.8	2.09	4.37
	35.3		2.9	7.59	57.61

$\sqrt{\frac{958.18}{8}}$ =10.9=S.D. single plot in per cent.

$\frac{10.9}{\sqrt{4}}$ =5.45=P.E. in per cent for 4 systematically distributed plots by the deviation from the mean of the variety method.

It is apparent in the illustration given that Plot 2 in each variety was in a favorable position and that there is some correlation in yielding ability of neighboring plots.

The criterion of the accuracy of the method is a comparison with probable errors obtained from the yields of check plots of a standard variety where the probable error $= \pm .6745\sqrt{\frac{\Sigma(d^2)}{n}}$.

Results obtained from a six-year comparison of the two methods are presented in Table I.

TABLE I

PROBABLE ERRORS OF A SINGLE PLOT TEST AS OBTAINED FROM CHECK PLOTS OF A STANDARD VARIETY AND FROM A COMBINATION OF OTHER VARIETIES IN THE TRIAL*

Crop	Year	Check plot method (Single standard variety)			Deviation of mean method (All varieties)		
		Av. yield	No. plots	P.E.	Av. yield	No. deviations	P.E.
		Bu.		Per cent	Bu.		Per cent
S. wheat	1919	20.3	42	11.8	20.0	108	15.2
	1920	25.8	60	10.1	25.0	252	9.6
	1921	18.6	44	10.2	17.8	140	10.2
	1922	35.4	52	9.2	33.8	292	8.6
	1923	30.9	26	5.2	32.2	360	5.7
	1924	26.9	64	9.0	25.7	328	9.9
Average		26.3		9.3	25.8		9.9
Oats	1919	56.4	48	7.6	62.3	132	6.1
	1920	80.7	42	9.2	77.1	788	9.4
	1921	50.7	43	7.5	51.8	388	7.9
	1922	115.6	55	4.7	100.6	160	5.1
	1923	61.6	55	7.0	61.0	579	6.1
	1924	59.0	60	10.4	58.3	292	6.7
Average		70.7		7.7	68.5		6.9
Barley	1919	41.9	52	9.5	29.7	80	9.2
	1920	49.1	32	10.0	41.5	188	10.1
	1921	30.9	62	10.0	28.1	232	9.6
	1922	60.7	48	11.6	60.4	520	10.1
	1923	56.1	34	7.1	54.1	324	7.5
	1924	42.5	24	7.9	40.8	76	8.6
Average		46.9		9.4	42.4		9.2
W. wheat	1924	45.2	24	5.3	45.6	88	5.1

* Miss Alma Schweppe, Fred Griffee, and H. E. Brewbaker assisted in the computations.

The two methods of computation gave very similar results. The average for the six-year period where the probable errors for the check plot method are given first and for the deviation of the mean method next are as follows: for wheat 9.3%, and 9.9; for oats 7.7 and 6.9; and for barley 9.4 and 9.2. The only differences of any magnitude were in 1919 in which case the probable errors by the two methods are 11.8 and 15.2, respectively, for wheat; and in 1924, 10.4 and 6.7, respectively, for oats. Only a single year's comparison is given for winter wheat as in other years winterkilling, occurring in spots in the nursery, prevented obtaining probable errors of any significance. Probable errors in percentage obtained by the two methods in the season in which winterkilling was not a factor are 5.3 and 5.1, respectively.

THE USE OF A PROBABLE ERROR IN ELIMINATING VARIETIES

As pointed out in an earlier paper (5) there is good agreement in general between mathematical expectation and actual reduction in the size of the probable error which is obtained by replication. To determine the probable error for several replicated plots the probable error in percentage calculated for a single plot is divided by $\sqrt{n}$ where n=the number of systematically distributed plots. This formula assumes a lack of correlation of yields of plots used in the computations. Probably such an assumption has no serious error in these studies altho there is, as will be shown later, correlation between the yielding ability of plots which are at some distance from each other. To determine the probable error for a series of years percentages are used and an average probable error is obtained by the formula $\frac{1}{N}\sqrt{a^2+b^2 \ldots\ldots n^2}$ where N=number of means averaged and a, b, n=separate probable errors in percentage for the respective years.[3]

The use which is made of such a probable error for the rod-row trials for any particular season may be illustrated by the probable error application the first year in which a large number of new rust-resistant hybrid oat lines were grown in the trials.

Two varieties of mid-season oats, Minota (Minn. No. 512) and Victory (Minn. Accession No. 514), have consistently proved the most desirable for central Minnesota. Both are good yielders, stand up better than the average, and, in general, are otherwise desirable except that they are highly susceptible to black stem rust, *Puccinia graminis avenae*. Erikss. and Henn. White Russian, which has received the variety name White Tartar (Etheridge, 1) is highly stem rust resistant in Minnesota but is late in maturity and on the average yields less than either Victory or Minota. From crosses between White Russian with either Victory or Minota, homozygous resistant lines were selected which were apparently homozygous in other characters. Approximately 1000 lines were grown in F_5 and a considerable number were discarded on the basis of undesirable appearance. The better homozygous lines were placed in rod-row trials in the sixth generation after the cross.

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[3] See Mellor, J. W., "Higher mathematics for the students of chemistry or physics," pp. 498-566. Longmans, Green, and Co.: New York and London. 1916.

At University Farm, St. Paul, each variety in the rod-row trial is, as a rule, grown in four systematically distributed plots of three rows each. A foot is cut off from the end of each row and the center row only of each three-row plot is used for the yield test.

In 1923, there were 176 lines in rod-row trials which were obtained from either White Russian x Minota or White Russian x Victory crosses. The highest yielding line produced 73.4 bushels, while the lowest produced 48.1 bushels. Some varieties could be discarded on the basis of undesirable plant or grain characters but the greater part could be discarded only on a yield basis.

The calculated probable error for three systematically distributed plots was $\frac{6.1}{\sqrt{3}}=3.5$ per cent (see Table I). Only three plots were used in 1923 because of the large number of new strains in the test.

On the basis of their probable errors any two varieties could be compared. The yields of Minota and of a hybrid which yielded somewhat less might be compared in the following manner:

The yield of Minota was 60.7 ± 2.1. Multiplying 2.1 by $3 \text{x} \sqrt{2}$ gives 8.8. By subtracting 8.8 from the yield of Minota a yield of 52.9 results. The chances are 22:1 that any variety yielding less than 52.9 is a lower yielder than Minota, there being only six such varieties. Adding 8.8 to 60.7 gives 69.5 bushels and there were only eight varieties which yielded more than this figure. The probable error in yield for these studies for a three-plot trial was 3.5 per cent which is much lower than is usually reported for such studies. However, out of 176 varieties the chances are 22:1 that eight were better yielders than Minota and that seven were inferior. On this basis it appears very apparent that very few, if any, varieties for this year could be discarded legitimately on a probable error basis. This is exactly what further studies with this material have shown. While varieties have been discarded from time to time this was done largely on the basis of plant and grain characters and not on a probable error basis, for very few varieties were consistently better or inferior to Minota and Victory in yielding ability. The question arises, did the probable error prove valuable in this study? Stem rust was not a factor at University Farm and the conclusion appears legitimate that many varieties have as high yielding ability as Minota or Victory and are known from other trials to be highly rust resistant. Somewhat greater confidence can be placed in the results than if the extent of error from soil heterogeneity was not known.

While in some cases a few varieties can be discarded on a probable error basis for a single year, without danger of eliminating the more desirable ones, most new strains must be tested for several years before discarding on a yield basis alone. Often new strains can be eliminated on the basis that they are much inferior in some important character such as strength of straw or susceptibility to disease. After two or more years some strains can, as a rule, be discarded because of low yielding ability, however, after a three year's trial a somewhat better basis of comparison is available.

Since 1920 the chief studies in barley breeding at University Farm, St. Paul, have had as their main purpose the obtaining of a smooth-awned variety of high-yielding ability which also excelled in other characters. Seventeen smooth-awned strains grown in comparison with Manchuria (Minn. No. 184) for from 2 to 5 years remain in the trials and many others have been discarded. The three varieties that have been tested for 5 years yield as much as Manchuria 184 and one variety, named Velvet, somewhat exceeds Manchuria.

Probable errors for four systematically distributed plots for different years have been computed by the deviation from the mean method.

Year	P.E. in per cent
1920	5.1
1921	4.8
1922	5.1
1923	3.8
1924	4.3
1920-24	2.1
1921-24	2.3
1922-24	2.6
1923-24	2.9

To determine the probable error for Velvet, which yielded an average for the 5 years of 52.6 bushels, multiply by the average probable error or 2.1 per cent. This gives a probable error of 1.1 bushels. Comparing Velvet and Manchuria on a 5-year basis the results are as follows:

Varieties compared	Average yield	Diff./P.E.
Velvet, Minn. 447	52.6±1.1	
Manchuria, Minn. 184	47.9±1.0	
Difference	4.7±1.5	3.1

The chances are about 26:1 that Velvet is superior to Manchuria, Minn. 184.

The same varieties may be compared by Student's method:

Manchuria	Velvet	D	D′	D′²
42.5	37.5	—5.0	11.7	136.89
56.1	61.8	+5.7	1.0	1.00
61.2	73.2	12.0	5.3	28.09
30.6	32.4	1.8	4.9	24.01
49.0	58.2	9.2	2.5	6.25
		5|33.7		5|196.24
		6.7		39.25

$Z=\frac{6.7}{6.3}=1.06$ S.D.$=\sqrt{39.25}=6.3$

On this basis the chances are ~~18.7~~ 9.4:1 that Velvet is a better yielder than Manchuria. However these varieties were not grown in paired plots and the only kind of paired comparisons that are available are seasonal. To the writer it appears that a probable error which measures soil heterogeneity is more desirable than Student's comparison for results of this nature.

Six smooth-awned strains have been compared with Manchuria for 5 years (1921-24, inclusive). All yield as well as Manchuria. The higher yielder is compared here with Manchuria.

Variety	Av. yields 1921-24	Diff./P.E.
Smooth Awn x Manchuria, II-21-14	54.4±1.4	
Manchuria, Minn. No. 184	47.6±1.2	
Difference	6.8±1.8	3.8

The chances are 95:1 that II-21-14 is a better yielder than Manchuria.

These two varieties may be compared by Student's method.

Year	Manchuria Minn. 184	Smooth-Awn x Manch. II-21-14	D	D′	D′²
1921	42.5	47.1	4.6	2.2	4.84
1922	56.1	55.9	—0.2	7.0	49.00
1923	61.2	64.5	3.3	3.5	12.25
1924	30.6	49.9	19.3	12.5	156.25
			4|27.0		4|222.34
			6.8		55.59

$Z=\frac{6.8}{7.5}=0.9$ S.D.$=7.5$

The chances are 8.22:1 that the hybrid is the better yielder. If, on the other hand, the hybrid had yielded in 1924, 33.8 bushels instead of 49.9 the chances would have been 32.2:1 that the hybrid was the better yielder. Results of this nature have been emphasized strongly by Salmon (13) and it seems evident to the writer that when a probable error for the experiment can be computed that a more logical comparison can be made between varieties growing in rod-row trials than by the use of Student's comparison. Both comparisons given here are taken at random without attempting to find cases where one method indicated the probability of a difference and the other failed to indicate such a probability.

In using a probable error computed by the deviation from the mean method it should be emphasized that such computations are not warranted when dealing with varieties widely different in adaptability, for in such cases it is evident from experimental data [Salmon (12), Stadler (14)] that one variety may be signfiicantly more variable than the other.

In both comparisons of the deviation from the mean and Student's methods the chances were somewhat greater by the deviation from the mean comparison that the varieties were significantly different than when made on the basis of Student's method. On the basis of a strict mathematical requirement the probable error would be decreased from that given by the deviation from the mean method for in the comparisons the correlation coefficient was not used in the determination of the probable error of a difference. The extent of error on this basis may well be pointed out.

THE CORRELATION IN YIELDING ABILITY OF NEARBY PLOTS IN ROD-ROW TRIALS

Harris (3, 4) has emphasized the fact that soil heterogeneity is often very large even on fields appearing highly uniform and has suggested a method of determining the degree of soil heterogeneity by the correlation in yielding ability of contiguously grouped plots. The method is of interest as a means of emphasizing the importance of the factor of soil heterogeneity but as the field must be cropped to a single variety it prevents its use for experimental purposes during the years in which the extent of soil heterogeneity is to be determined. The method furnishes the experimenter with a convenient tool to measure the relative heterogeneity of two fields, thus enabling the selection of the more uniform soil for plot trials.

It is desirable in some cases to measure heterogeneity and still carry on plot or varietal trials at the same time. The following study indicates one way in which this can be done.

As has been previously mentioned four systematically distributed plots are used, as a rule, for the rod-row trials conducted at University Farm. These are commonly grown in the same order in each replicated series. There was considerable evidence in 1924, by an examination of the relative vigor of plant growth, that some sections of the field on which the wheat and oat rod-row trials were being conducted were inferior to others. The yield of each plot of each variety was placed on a percentage basis, the average yield of each four plots being taken as 100. Correlation coefficients were then computed to express the degree of relationship for yielding ability of adjacent plots and for plots separated, respectively, by 1, 2, 3, 4, and 10 intervening plots.

The rows were sown lengthwise of the field and each series of rows was separated from the next series by a three-foot alley. By cutting off one foot from the end of each row, the border effect was minimized, as has been explained, and the central row of each three-row plot was harvested. The yielding ability of each plot was expressed in percentage and only plots lying in the same series were used for the correlations. In the various computations the 16-foot row plots were separated from each other by 3, 6, 9, 12, 15, and 30 feet, respectively.

The correlation coefficients as computed are presented in Table II together with regression equations.

The respective coefficients for the extent of soil heterogeneity in adjacent plots in spring wheat, oats, and winter wheat were .618±.023. .572±.025, and .552±.068, respectively. In spring wheat the extent of heterogeneity for plots separated by 6, 9, 12, 15, or 30 feet was practically the same or slightly more than .4.

TABLE II

Correlation of Percentage Yielding Ability in Nearby Plots of Oats, Winter Wheat and Spring Wheat, 1924

Crop	Correlation of	Correlation coefficient	Means		Standard deviations		Regression equation
			X	Y	X	Y	
Oat rod rows	Adjacent plots	.572±.025	100.14	99.79	10.18	10.04	$Y=43.30+.5641X$
	Separated by 1	.490±.029	100.07	99.37	10.00	9.81	$Y=51.27+.4807X$
	Separated by 2	.407±.034	100.25	99.38	9.94	9.72	$Y=59.48+.3980X$
	Separated by 3	.412±.035	100.51	99.46	10.09	9.55	$Y=60.26+.3900X$
	Separated by 4	.264±.041	100.43	99.30	10.36	9.61	$Y=74.70+.2449X$
	Separated by 10	.275±.057			10.65	8.18	
Winter wheat rod rows	Adjacent plots	.552±.068					
	Separated by 1	.293±.093					
	Separated by 4	—.114±.118					
Spring wheat rod rows	Adjacent plots	.618±.023	99.74	99.74	13.90	13.95	$Y=37.85\pm.6205X$
	Separated by 1	.518±.028	99.76	99.77	14.02	14.05	$Y=47.99\pm.5191X$
	Separated by 2	.454±.030	99.74	99.90	14.16	14.18	$Y=54.56+.4546X$
	Separated by 3	.383±.034	99.75	99.93	14.32	14.48	$Y=61.30+.3873X$
	Separated by 4	.449±.034	99.84	100.00	14.40	13.95	$Y=56.72+.4350X$
	Separated by 10	.429					

Note.—All computations were checked. H. E. Brewbaker, W. C. Broadfoot, C. H. Goulden, K. S. Quisenberry, S. C. Salmon, George Stewart, D. W. Robertson, and Miss Alma Schweppe assisted in the computations.

With oats, plots separated by 4 or 10 intervening plots had a soil heterogeneity relationship which was expressed by a coefficient of approximately .27 while the relationship between plots separated by 1, 2, or 3 intervening plots was not greatly different than in the spring wheat trials. For winter wheat, adjacent plots showed rather high heterogeneity while plots separated by several feet did not exhibit any soil heterogeneity relationship. By duplicate planting of experimental rod-row, varietal, or strain trials on two separate fields it would be possible to compare soil heterogeneity and determine the most desirable field and in the same season to conduct a yield comparison.

Richey (11) has given the reduction in variability which may be expected from using the regression equation to correct yields on the basis of adjusting to a moving average. He states that correlations of less than .6 will reduce variability so little that adjustment may hardly be worth while altho in some cases it is emphasized that adjustment may materially change the relative standing of a variety, all four plots of which may happen to be placed on relatively poor or good soil.

Table III is taken from Richey's publication.

TABLE III

EXPECTED REDUCTION IN VARIABILITY FOR VARIOUS CORRELATION COEFFICIENTS (RICHEY)

$r=$	Reduction in variability= $100\times 1-\sqrt{1-r^2}$	$r=$	Reduction in variability= $100\times 1-\sqrt{1-r^2}$
	Per cent		Per cent
0.4	08.4	0.8	40.0
0.5	13.4	0.866	50.0
0.6	20.0	0.9	56.4
0.707	29.3	1.0	100.0

In the spring wheat and oats studies check plots of standard varieties were distributed through the test every 6 plots. The yields of each plot of nearby varieties were adjusted by means of the regression values. The method used is illustrated for several plots in the wheat series.

Plot No.	Actual yield	Percentage yield
Check a	25.1	93
8	27.5	
9	20.3	
10	28.3	
11	24.2	
12	25.7	
Check b	32.2	120

The yielding ability of each check plot was expressed in percentage by dividing its actual yield by the average of all check plots. By this method the yielding ability of Check a was 93 and of b, 120.

If y=nearby plot and x= the check, then the corrected percentage yielding values for Plot 8 would be

$$1.\quad y = 37.85 + .6205\ x = 95.56$$

$$2.\quad y = 56.72 + .4350\ x = 108.92$$

A value of 102 was obtained by adding 1 and 2 and averaging. The corrected yield for Plot 8 in bushels would then be obtained by dividing the actual yield, 27.5 bushels, by 102. In this way the yield of each plot of each variety was adjusted by the yield of the two nearest check plots on the basis of the average relationship as expressed by the calculated regression equations.

After obtaining a corrected yield for each plot of all varieties, except the check plots, a probable error in percentage was calculated by the deviation from the mean method. These probable errors were then compared with probable errors obtained before adjustment. The results are presented in Table IV.

TABLE IV

Probable Error for a Single Plot Test before Adjustment of Yields and after Correcting Yields on the Basis of the Regression Values and in Relation to the Two Nearest Check Plots

Crop	Probable error in percentage	
	Actual yield	After correction
Spring wheat	9.9	8.0
Oats	6.7	5.8

The actual percentage probable errors are reduced by adjustment to a moving average by approximately 19 and 13 per cent, respectively, which is slightly more than expected on the basis of the standard error of estimate for correlation coefficient of the values obtained. It seems very doubtful whether the reduction in probable error is worth the trouble of making the calculations.

The actual and corrected yields and the relative standing of varieties before and after correction are given in Tables V and VI.

TABLE V

Comparison of Yields and Relative Standing of Strains before and after Correction on the Basis of the Relation Expressed by the Regression Equation

Spring Wheat Rod Rows, 1924

Variety	Yield range after correction	Yield range before correction	Difference + or —	Range after correction	Range actual
II-18-20	32.7	32.7	0.0	1	1
B2-5	30.7	31.5	—0.8	2	2
II-18-44	30.6	31.2	—0.6	3	3
II-17-40	30.0	30.9	—0.9	4	4
II-15-41	29.9	29.7	+0.2	5	10
II-18-21	29.8	29.5	+0.3	6	12
II-17-45	29.7	30.5	—0.8	7	5
B8-11	29.6	29.9	—0.3	8	7
II-18-8	29.6	30.3	—0.7	9	6
II-15-13	29.5	29.6	—0.1	10	11
Ruby	29.3	29.8	—0.5	11	9
II-18-33	29.2	28.6	+0.6	12	18
II-15-24	29.0	29.0	0.0	13	15
II-18-15	28.8	29.8	—1.0	14	8
II-17-37	28.7	29.4	—0.7	15	13
N.D. 149.124	28.7	28.6	+0.1	16	21

TABLE V—*Continued*

Variety	Yield range after correction	Yield range before correction	Difference + or −	Range after correction	Range actual
II-17-23	28.4	28.7	−0.3	17	17
II-17-36	28.2	29.0	−0.8	18	14
II-15-16	28.1	28.1	0.0	19	23
II-17-43	28.0	28.6	−0.6	20	19
II-15-57	28.0	28.6	−0.6	21	20
II-17-22	27.9	28.4	−0.5	22	22
II-15-8	27.9	28.7	−0.8	23	16
II-17-4	27.7	27.0	+0.7	24	27
II-18-17	27.6	27.8	−0.2	25	24
II-17-3	27.2	26.4	+0.8	26	30
N.D. 149.43	27.2	27.0	+0.2	27	26
II-19-11	26.6	27.5	−0.9	28	25
II-18-28	26.5	25.7	+0.8	29	40
II-15-39	26.4	26.1	+0.3	30	35
N.D. 149.178	26.4	26.2	+0.2	31	33
II-18-19	26.2	26.3	−0.1	32	31
II-17-33	26.2	27.0	−0.8	33	28
Kitchener	26.2	26.2	0.0	34	34
II-19-2	26.1	26.6	−0.5	35	29
Red Bobs	26.0	26.1	−0.1	36	36
II-18-27	25.9	25.6	+0.3	37	41
II-17-2	25.8	26.2	−0.4	38	32
II-19-9	25.7	25.4	+0.3	39	44
II-18-36	25.4	25.9	−0.5	40	37
II-17-28	25.4	25.9	−0.5	41	38
II-17-25	25.1	25.4	−0.3	42	45
II-17-35	25.1	25.6	−0.5	43	42
II-17-14	24.9	24.0	+0.9	44	54
II-18-12	24.9	25.5	−0.6	45	43
Kota Bulk	24.7	24.2	+0.5	46	49
II-19-19	24.7	25.3	−0.6	47	46
II-19-23	24.6	24.1	+0.5	48	52
II-18-16	24.6	25.8	−1.2	49	39
II-17-13	24.5	23.6	+0.9	50	59
II-18-34	24.4	24.0	+0.4	51	53
II-18-35	24.3	23.9	+0.4	52	55
II-18-38	24.3	24.6	−0.3	53	48
II-18-39	24.3	24.7	−0.4	54	47
II-19-26	24.0	23.7	+0.3	55	56
N.D. 149.48	24.0	23.7	+0.3	56	57
II-17-15	23.8	23.1	+0.7	57	60
II-17-8	23.7	23.0	+0.7	58	61
II-19-12	23.6	24.2	−0.6	59	50
II-19-18	23.4	24.2	−0.8	60	51
II-17-20	23.4	22.6	+0.8	61	63
II-18-37	23.3	23.6	−0.3	62	58
II-17-10	23.2	22.5	+0.7	63	64
II-17-7	23.0	22.4	+0.6	64	65
N.D. 149.1	22.9	22.9	0.0	65	62
II-17-16	22.0	21.4	+0.6	66	68
II-17-19	21.8	21.1	+0.7	67	69
II-19-29	21.6	21.4	+0.2	68	67
II-17-29	21.5	22.3	−0.8	69	66
II-15-55	20.9	20.7	+0.2	70	70
II-15-59	20.9	20.6	+0.3	71	71

TABLE VI

Comparison of Yields and Relative Standing of Strains before and after Correction on the Basis of the Relation Expressed by the Regression Equation

Oat Rod Rows, 1924

Variety	Yield range after correction	Yield range before correction	Difference + or −	Range after correction	Range actual
II-18-149	72.0	73.3	−1.3	1	1
II-18-114	67.4	68.4	−1.0	2	3
II-18-224	66.6	67.7	−1.1	3	5
II-19-7	66.3	68.1	−1.8	4	4
II-18-150	66.0	68.9	−2.9	5	2
II-18-222	65.7	66.2	−0.5	6	10
II-18-238	65.0	66.5	−1.5	7	9
II-19-4	64.9	66.5	−1.6	8	8
II-18-157	64.8	66.9	−2.1	9	6
I-06-12	64.5	65.9	−1.4	10	11
II-18-171	64.2	65.5	−1.3	11	12
II-19-5	63.4	66.6	−3.2	12	7
II-18-227	63.4	65.1	−1.7	13	13
II-18-221	63.4	62.6	+0.8	14	22
II-18-153	62.2	64.4	−2.2	15	14
II-18-100	62.0	63.0	−1.0	16	19
II-18-108	62.0	62.9	−0.9	17	20
II-19-2	61.8	63.2	−1.4	18	16
II-19-8	61.8	63.7	−1.9	19	15
II-19-6	61.8	63.3	−1.5	20	17
II-18-225	60.8	62.2	−1.4	21	23
II-18-169	60.5	61.5	−1.0	22	25
II-18-152	60.5	63.0	−2.5	23	18
II-19-9	60.3	61.8	−1.5	24	24
II-18-163	60.3	60.9	−0.6	25	27
II-18-151	60.3	62.9	−2.6	26	21
II-18-147	60.1	60.7	−0.6	27	28
II-18-185	59.8	55.2	+4.6	28	46
II-18-148	59.3	61.0	−0.7	29	26
II-18-23	59.2	58.0	+1.2	30	35
II-18-178	58.9	59.7	−0.8	31	30
II-18-228	58.9	59.6	−0.7	32	31
II-18-226	58.5	60.1	−1.6	33	29
II-18-8	58.5	56.8	+1.7	34	38
II-18-161	58.1	58.9	−0.8	35	33
II-18-20	58.1	56.4	+1.7	36	41
II-18-194	57.8	54.6	+3.2	37	48
II-18-18	57.6	55.9	+1.7	38	43
II-19-10	57.1	58.6	−1.5	39	34
II-18-15	57.0	54.9	+2.1	40	47
II-18-155	56.9	59.1	−2.2	41	32
II-18-187	56.7	52.4	+4.3	42	56
II-18-180	56.7	56.5	+0.2	43	39
II-18-193	56.5	53.3	+3.2	44	52
II-18-37	56.5	55.4	+1.1	45	45
II-18-181	56.3	55.7	+0.6	46	44
II-18-145	56.3	57.2	−0.9	47	36
II-18-179	56.1	56.0	+0.1	48	42
II-18-12	55.9	53.9	+2.0	49	49
II-18-146	55.8	56.4	−0.6	50	40
II-18-14	55.6	53.6	+2.0	51	51
II-18-158	55.4	56.9	−1.5	52	37
II-18-19	55.4	53.6	+1.8	53	50
II-18-188	55.3	51.3	+4.0	54	62
II-18-189	55.3	51.7	+3.6	55	59
II-18-184	54.9	51.3	+3.6	56	61
II-18-200	54.8	52.8	+2.0	57	53

TABLE VI—*Continued*

Variety	Yield range after correction	Yield range before correction	Difference + or —	Range after correction	Range actual
II-18-183	54.8	51.5	+3.3	58	60
II-18-195	54.7	52.3	+2.4	59	57
II-18-186	54.6	50.8	+3.8	60	64
II-18-196	54.4	52.6	+1.8	61	55
II-18-13	53.9	52.0	+1.9	62	58
II-18-190	53.8	50.5	+3.3	63	65
II-18-201	53.1	52.6	+0.5	64	54
II-18-6	52.8	51.1	+1.7	65	63
II-18-197	52.4	50.4	+2.0	66	66
II-18-199	51.9	49.9	+2.0	67	68
II-18-198	51.8	49.9	+1.9	68	67
II-18-3	49.6	48.6	+1.0	69	70
II-18-74	49.2	48.8	+0.4	70	69
II-18-60	44.5	43.7	+0.8	71	71

Relative standing of the varieties is changed very little by correction of yields. In the spring wheat the four highest yielders remain in the same relative order after correction as before. Varieties which after correction stood 5 and 6 were tenth and twelfth, respectively, on the basis of actual yield. The greatest change in yielding value was only 1.2 bushels, whereas the probable error for a four-plot trial is 5.0 per cent and for a yield of 25 bushels the probable error in bushels is 1.25. The greatest change in yielding value for spring wheat was about the same as the probable error.

With oats there were several cases where changes in yielding value were relatively somewhat larger than with wheat. The greatest change as a result of correction was 4.6 bushels. This is slightly more than two times the calculated probable error.

In no case is the relative change in yielding ability of particular significance and the correction of yields in such studies, which must be continued for three years at least, and where the better strains will be compared for a six-year period in several localities, appears to be of little value. Correction of yields on the basis of regression values and in relation to a moving average will certainly, where soil heterogeneity is a factor, reduce to some extent the size of the probable error.

SUMMARY

1. A probable error for the experiment measures on the average the extent of error of a non-systematic nature. It measures chiefly errors which arise from soil heterogeneity or other uncontrolled errors of like nature. The method of calculation rests on the assumption that all varieties are equally variable. This is not true for widely different varieties, however, in plant breeding experiments most varieties are rather similar in general adaptability. This is perhaps particularly true

when the Mendelian mode of attack for the synthesis of new varieties is used.

2. In plant breeding studies such as rod-row trials in which several systematically distributed plots are used and where all varieties or strains are similar in general adaptability the combined probable error as obtained from all varieties, by some such method as the "deviation from the mean," was found to be very similar to that obtained from check plots.

3. By expressing probable errors for different seasons in percentage an average for several seasons can be computed. Varieties can be compared for various yearly tests and for combined tests. Better yielding varieties can then be determined and the probabilities that they are significantly better than others can be measured accurately. Such methods, if correctly understood, should lead to more accurate and scientific comparisons.

4. The use of Student's method for varietal trials conducted for several years is not entirely satisfactory as there is no sure control or measure of soil heterogeneity unless the comparisons are made on the basis of adjacent plots. Student's method is valuable for trials where it may be expected that if there is a difference in yielding ability the difference will be consistent from year to year. Such consistence is not commonly obtained in varietal tests. Differences which are a result of varietal resistance or susceptibility and which are only apparent under disease infection conditions may be present only once in every three or four seasons. Student's method used for seasonal averages tends to cover up important differences.

5. By the deviation from the mean method calculated on the basis of numerous strains the odds that two varieties were different in yielding ability for a four- and five-year trial, respectively, were much greater than where Student's method was used and seasonal averages were compared.

6. Adjustment of yields by the regression equation on the basis of a moving average leads to a reduction in the probable error of the experiment providing soil heterogeneity is a factor. If the extent of soil heterogeneity as measured by the correlation coefficient is .6 or lower and if the probable error of a single determination is 10 per cent or less, adjustment of yields will, as a rule, not markedly change the relative standing of varieties. Such changes as occur will be of little importance on the average.

7. An estimate of the extent of soil heterogeneity may be accomplished by placing the yields of each separate set of replications of individual strains on a percentage basis with 100 as an average. By the correlation of yielding ability of plots which are separated by any

particular number of intervening plots the extent of soil heterogeneity may be measured. By placing a similar series of varieties on each of two fields the one with the least soil heterogeneity can be selected for permanent nursery experiments.

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Agricultural Experiment Station

A Study of a Disease of the Bones and Joints of Swine

An Osteo-Arthropathy

H. C. H. Kernkamp
Division of Veterinary Medicine

UNIVERSITY FARM, ST. PAUL

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A STUDY OF A DISEASE OF THE BONES AND JOINTS OF SWINE, AN OSTEO-ARTHROPATHY

By H. C. H. Kernkamp

INTRODUCTION

A disease of swine characterized by certain paretic-like symptoms has attracted much attention in recent years. A disease of this nature, aside from "sow paralysis," was either infrequently observed or little discussed a few years ago. Such cases of paralysis were looked upon as "rheumatic conditions" in many instances. In others the paretic-like symptoms were regarded as the manisfestation of some kidney disturbance or the sequela of an injury. Rickets and "posterior paralysis" are terms often applied to a condition showing symptoms as described.

The material presented in this study includes the results of experimentation and research, together with observations made on specimens sent to the laboratory, also results of examinations made on a number of farms where the disease existed. Many farms were visited and several examinations made before any experimentation was started.

Before planning the experiment, the data obtained from a number of field investigations were analyzed. A study of the anamneses, clinical and necropsy findings in each case indicated that the disease was of nutritional or trophic origin.

A second analysis of the data showed that various combinations of foodstuffs constituted the swine rations on the several farms. (Refer to protocols for specific rations.) A summary showed that the following foodstuffs were used: cereals fed as whole grains, including corn, oats, and barley; mill feeds, including shorts, bran, red dog flour, ground oats, ground corn, ground barley, and mill sweepings; commercial concentrates, including oil meal and tankage; dairy products, including whole milk, skimmilk, and buttermilk (creamery run or semisolid). Alfalfa, red clover, rape, blue grass, and rye represented the green foods where pasture was used. That which was called pasture in some cases amounted to nothing more than an exercising pen, the ground being barren and devoid of vegetation—strict "dry lot" conditions. A plank-floored enclosure was the only out-of-doors pen available in one case. Kitchen slops were utilized in some cases and on one farm a commercial stock food was being fed.

Component parts of the various rations were next considered, i.e., proteins, fat, carbohydrates, minerals, and the accessory food factors or vitamins. A few of the rations could be criticized as lacking in protein, and others because of the quality of the proteins. An abundance of carbohydrates was found where the nitrogenous substances were low. In no cases were diets deficient in carbohydrates. The antiscorbutic or water soluble vitamin (C) was noticeably missing in some of the rations. However, it is questionable as to just what significance this vitamin has in connection with avitaminoses in farm animals. All of the rations supplied some of the Vitamins A and B. All rations which did not provide green pasture as a part of the diet were also deficient in the antirachitic vitamin. Many severe cases of an osteo-arthritic disease were observed, however, on farms where all these elements were being supplied in abundance. (See Protocol 6.) A lack of calcium seemed to be the outstanding mineral deficiency in many cases. Yet there were typical cases of a bone and joint disease in swine which were receiving foodstuffs that are said to carry large quantities of calcium. (Compare Protocols 6 and 7.)

EXPERIMENTAL WORK

Experimental work was begun in March 1921 and continued to the latter part of 1923. The pigs used in these trials were purchased at the South St. Paul stockyards and were from 4 to 5 months of age. They were brought to University Farm, immunized against hog cholera by the serum-virus method and kept in a 21-day quarantine before placed in the experimental lots. During this period a ration of corn, oats, red dog flour, and tankage was fed. The pigs were fed just enough of these foodstuffs to keep them at about an even weight. All pigs were in good physical condition at the end of this period, as far as could be determined. Each pig was ear-tagged and placed in a lot or group just before the experiment. The lot or group was based on weight, size, breed, and sex of each pig, and, as far as possible, the lots were equally balanced.

EQUIPMENT

Throughout the experimental period, except for the time required for weighing, the pigs were kept in pens in a large shed or barn. Each pen covered an area of approximately 200 square feet. The pen partitions were made of wood. On the south wall of each pen was a 30x40 inch window. These were closed only in inclement weather. The floors were of cement, troweled, smooth, and drained to one end. Each pen contained two V-shaped wood troughs, one for water and the other for feed. The scale for weighing the pigs was in a separate building about 50 feet distant. Once every 10 days the pigs were driven to these scales and weighed as expeditiously as possible. They were removed from the pens at no other time. Separate bins were constructed for each diet mixture. Separate feed pails and scoops were provided, one for each diet mixture. Feed scales and charts were convenient for the caretaker.

Diet mixtures were compounded in from 200 to 400 pound lots. The constituents of each lot were weighed separately then dumped together and mixed thoroly. The mixture was agitated again when about half had been fed. The pigs were fed twice a day, morning and evening. The amount of feed for each lot at each feeding was weighed and recorded. Oat straw bedding was kept in one half of each pen at all times.

DIETS (RATIONS), LOTS, AND RESULTS

Diet 1

The basal ration or Diet 1 was compounded according to the following formula:

Corn	99 parts
Sodium chloride	1 part

Obviously, this is a poor ration. That such a ration is deficient and unbalanced has been known for a long time, yet it is a fact that a great many farmers feed swine rations almost identical with it. Rations of similar character have been used by other investigators (1) who have concluded that unless corn is supplemented it is not a good diet for growing swine.

The principal deficiency of this diet is the lack of protein. Zein, the principal protein of corn, is not a complete protein, as it is deficient in some of the amino acids essential for maintenance and growth, notably lysin and tryptophan (2). The diet is also low in mineral matter, particularly in calcium. According to Henry and Morrison (3) there are only .2 of a pound of calcium to every 1000 pounds of shelled corn. On the other hand, the phosphorus content of corn is quite high—6.9 pounds per 1000. Yellow corn is a good source of Vitamins A and B, and yellow corn was used throughout these experiments.

Four different lots of pigs (I, V, VII, XI), comprising 24 in all were fed Diet 1. Lot I was under experiment from April until August, 1921; Lot V from August until the middle of December, 1921; Lot VII, from January to April, 1922; Lot XI, in the spring of 1923.

The 8 pigs in Lot I averaged 97.5 pounds at the beginning of the experiment. Six, or 75 per cent, developed a disease of the bones and joints. In two, 9769 and 9781, the disease became very severe and marked evidence of arthritis and loss of function, akinesia algera, appeared (Fig. 1). The first evidence of disease was observed in 9781, 35 days after the beginning of the trial. Its average daily rate of gain for the 35 days was .5 of a pound. Following the appearance of first symptoms, this pig began to lose weight and continued to do so for the remainder of its life. The disease became so marked that after about the seventieth day it could not rise upon its feet.

The second pig to show symptoms was 9769. This was 40 days from the beginning of the feeding period. Up to the time of the first symptoms it was making an average daily gain of 1.25 pounds. It gained only 2 pounds in the next 10 days and from then it lost weight continually. The course of the disease paralleled that of Pig 9781.

In Pig 9762, which was gaining at a rate of only .24 pound per day, the first symptoms were noted on the forty-second day. The symptoms never amounted to more than a slight stiffness and a tendency toward a stilty gait. This pig did little more than maintain itself for the remainder of the experimental period. The three remaining pigs in this lot, in which symptoms appeared, did not show symptoms until after 60 days from the beginning of the trial. The disease progressed slowly, but before the end of the experiment they were very lame and sore. Throughout the trial they were gaining in weight at an average of one pound daily.

Two pigs in this lot never showed evidence of an osteo-arthropathy. One of them gained only 15 pounds in weight during the entire period, the other, 25 pounds. Only slight skeletal growth was observed in either of these pigs and in Pig 9762. Their hair coats were rough, harsh, and dry and a marginal area of skin about the eyes was very light in color and more or less scurfy.

The 5 pigs in Lot V at the beginning of the experiment weighed on an average of 83.3 pounds each. One was a Duroc-Jersey, one a Chester-White, and three were crossbred, Poland-Duroc. In this trial two, or 40 per cent, of the pigs developed characteristic symptoms. The first to show symptoms was Pig 9785. This was the fifty-fifth day. Up to this time .58 pound was its average daily gain and for the remainder of the period its weight remained about constant. This pig did not develop a marked case of the disease. Pig 9792, the second of the lot to show symptoms, gained 3 pounds the first ten days of the trial but then steadily lost weight. The stiffness and lameness which developed, involved only the left hind leg. They were first observed on the seventieth day.

Two of the pigs, 9786 and 9793, barely maintained themselves throughout the entire period, in this case 110 days. One of them at the end of the period weighed 2.5 pounds less than at the beginning, and the other gained only 13 pounds. The condition of these pigs was comparable to that of Pig 9762 of Lot I. The fifth pig of this lot did little better than the two preceding. It gained only 32.5 pounds and made slight skeletal growth. No clinical manifestations of disease were observed in any of these pigs.

Lot VII was the third group to receive the basal ration. The average weight of the seven pigs at the beginning of the trial was 72.6 pounds. They then all appeared well and healthy. Four of them were Poland-Chester-White crossbreds and three were grade Duroc-Jerseys. Between the forty-fifth and fifty-fifth day of the feeding period three of them sickened and died. An autopsy showed that the most marked lesions were those of broncho-pneumonia and hemorrhagic enteritis, with petechia on the laryngeal and bladder mucosa. Clinically they had shown marked prostration and weakness with high temperatures. It was felt that the principal factor operating in connection with these casualties was a hog cholera "break." The remaining pigs were given large doses of anti-hog cholera serum and no further losses occurred.

Of the four pigs left in the lot three developed symptoms of an osteo-arthropathy; on the forty-fifth day in one, on the forty-seventh day in another, and on the fifty-second day in the third. The disease in one case became severe; the other two were mild. None of the pigs increased much in weight or made appreciable skeletal growth. The fourth pig lost 20 pounds in the experimental period; no clinical symptoms were observed.

Five grade pigs averaging 79.5 pounds each comprised Lot XI, the fourth group to receive this ration. Two were Durocs, two Polands, and one was a Chester-White.

Three of these never showed signs of a bone and joint disease and for a period of 90 days, the duration of the trial, their average daily gain per pig was .56 of a pound. Their skeletal growth was proportionate.

Two pigs developed the disease. Pig 9889 became a marked case. The symptoms began with a lameness in the right thoracic limb. Later it was lame in all four legs. The progress of the disease was slow but in 40 days from the appearance of the first symptoms, it reached a point where total loss of locomotive function was evident. The first symptoms were observed on the thirtieth day. This pig increased in weight at a rate of .4 pound per day until the time when it could not get about the pen unassisted. The second pig of the lot to show symptoms was 9902. They were not observed until the seventy-second day. This case did not become severe. It gained 55 pounds in 90 days.

Diet 2

A second diet was formulated to compensate for the protein deficiency of the basal ration. For this purpose a commercial grade of casein was supplied. Casein (4) carries large amounts of tryptophan and lysin, the two amino acids deficient in zein. The ingredients and amounts of each constituting this ration were:

Corn	94 parts
Casein	5 parts
Sodium chloride	1 part

This ration was fed to nineteen pigs divided among three lots, II, IX, XIII.

Seven Duroc-Jersey pigs of good quality, averaging 94.4 pounds per pig, made up Lot II. This group was being fed at the same time as Lot I. Four pigs in Lot II made exceptionally good gains in weight. In fact, all made good gains in weight and increased in skeletal growth. After 100 days, the length of time that the pigs were kept on the experiment, each weighed on an average 242.8 pounds.

Four, or 57 per cent of the pigs in this lot, showed that some pathological process was operative in the bones and joints of the legs. Pig 9779, the first to show symptoms, developed a lameness and stiffness forty-one days from the beginning of the experiment. This progressed slowly, and later it required considerable urging by the caretaker to make this animal regain its feet. When walking the joints of the front legs were held immobile and a marked lameness of the left hind leg was evident. To stand or to walk caused this pig much pain. Notwithstanding the progress of the disease, this pig gained at a rate of .86 pound daily. The second pig in this lot to show symptoms was 9756. They were first noticed on the fifty-sixth day, and were particularly those of a shoulder lameness involving the right thoracic leg. This persisted throughout the trial.

Pigs 9764 and 9770 did not show definite clinical manifestations until the eighty-second and ninety-second days, respectively. These two pigs and the three others which never showed evidence of disease, made average daily gains of 1.6 pounds.

A point worthy of notice is that for the last 50 to 60 days of the feeding period all the pigs in this lot were more or less slow and sluggish in their movements. They were not excitable; on the contrary, they possessed a low temperament and were quiet and docile. Considerable urging and driving was necessary when taking them to or from the scales to be weighed. Their bodies were plump and smooth and their hair was sleek.

Lot IX, the second group to receive this ration, consisted of seven pigs. Results in this group were not the same as in Lot II. First, none of these pigs developed an arthritic or osseous disease. Second, as a group, their increase in skeletal growth and body weight was far below those of Lot II. In fact, they did not do as well as the groups fed Diet 1. This lot was being fed and cared for at the same time as

Lot VII, and a hog cholera break, as described for Lot VII, occurred in this group. Three pigs died; two others were very sick but later recovered. The remaining two were sick about one week and then recovered, and came back on full feed, continuing to gain at a rate of .5 pound per day. The two that recovered after being sick for a longer time weighed less at the end of the trial than at the beginning. It is quite probable that the complicating illness was responsible for the poor results obtained with this group.

Diet 2 was used a third time on a group of five pigs, Lot XIII. They averaged 83.5 pounds per pig when placed on experiment. Four of them were Duroc-Jerseys and one a Chester-White. All the pigs in this lot showed characteristic clinical manifestations of a bone and joint disease.

The first symptoms were observed in Pig 9907 on the fortieth day. Almost simultaneously with the onset of the symptoms the growth stopped and loss in body weight began and continued throughout the remainder of the period. The disease progressed and became so severe that by the eightieth day the pig could not stand up on its feet. The second to show symptoms was 9897. They were first noticed on the forty-sixth day. Up to this time the pig was gaining at a rate of 1.5 pounds per day, but like 9907, growth stopped and loss in weight began with the development of clinical symptoms. The disease progressed and by the end of 100 days the pig could not walk.

The next to show symptoms was 9905. They appeared on the sixty-fourth day and continued throughout the period. The disease, however, did not become severe in this case. The pig gained in weight at an average of 1.3 pounds per day up until the time of first symptoms. After this it lost weight continually.

The two remaining pigs showed a stiffened and stilty gait the last 30 days of the experiment. When they were standing the metacarpi were inclined downward and backward so that the front feet were placed farther under the body. These pigs gained in weight at approximately 1.8 pounds per day for the first 40 days. The following 30 days, or until the time the symptoms were noted, the rate of gain dropped to only .27 pound per day. They continued to gain at about this rate until they were taken off the experiment. Only a mild form of the disease was apparent in these pigs.

DIET 3

It seemed advisable to keep one lot of pigs on a diet carrying a liberal supply of the antiscorbutic vitamin (Vitamin C). For this reason the following ration was prepared:

Corn	99 parts
Sodium chloride	1 part
Cabbage, per pig per day............	1 pound

The white parts of cabbage were used because they contain an abundance of Vitamin C, and because the food could readily be obtained only sound heads of cabbage were used. They were chopped into small pieces and placed in the feed trough once each day, about three hours after the morning feeding of corn. One pound of the chopped cabbage per pig a day was more than the pigs would consume at all times.

This ration was fed to one group of pigs, consisting of seven Duroc-Jersey pigs weighing on an average 89.5 pounds per head. This group was designated Lot IV and was carried along with Lots I and II.

The first pig to show symptoms was 9765. These were observed on the twenty-fifth day. For the first two weighing periods, the average daily rate of gain for this pig was 1.25 pounds, but at the next weighing, 10 days later, the rate fell to .5 pound, and the pig continued to lose weight from then on. The progress of the disease was rapid, in 15 days from the first symptoms total loss of locomotive function had occurred. Each time the pig would try to move about, loud squeals were emitted, indicating much pain.

On the fifty-first day Pig 9780 was stiff and lame for the first time. Prior to this it had increased in weight 50 pounds. It gained only 10 pounds for the remainder of the period, 47 days. This pig became very stiff, lame, and sore in the two front and left hind legs. However, this case did not become as severe as the preceding one.

The other pig in this group to develop the disease was 9757. It was 60 days before the first symptoms were observed. The disease was not as marked as in 9780. The rate of growth and increase in skeletal structures did not appear to be influenced by the disease, since the rate remained the same after disease was evident as before.

The four remaining pigs of this lot showed no indications of disease. Three of them made average daily gains of approximately .75 pound and the fourth of .25 pound. The skins and hair coats were similar to those of Pig 9762 of Lot I, Diet 1.

Diet 4

Diet 4, containing an additional amount of calcium, was made up of:

Corn	97 parts
Calcium carbonate	2 parts
Sodium chloride	1 part

This ration made available approximately 380 grams of calcium in each 100 pounds of feed. There was almost 22 times as much calcium in Diet 4 as in Diets 1, 2, and 3. These figures do not take into account the amount of calcium consumed in drinking water. An analysis of the water at University Farm made by the division of agricultural biochemistry, showed that it contained 164.5 parts of calcium carbonate per million. No records were kept of the exact amounts of water the pigs drank but estimates based on relative amounts show that each pig received about .1 gram of calcium per day in water. This applies to all pigs in all lots.

Three lots of pigs received Diet 4. Seven grade Duroc-Jersey pigs averaging 94.6 pounds per pig at the beginning of the trial comprised Lot III. They were on experiment at the same time as Lots I, II, and IV. None of these pigs developed symptoms characteristic of the arthritic and osseous disease observed in pigs receiving the other three rations. Five pigs in the lot made good skeletal growth and increases in body weight. They gained on an average 1.09 pounds daily for 100 days. One gained at a rate of 1.48 pounds per day. This was very close to some of the pigs which received the protein supplement. Two pigs in the lot made little skeletal growth and increase in weight, their average daily gain being .31 pound.

An apparent interesting fact was that the pigs in this group always showed a lively temperament. When a person walked among them in the pen and when driven to the scales, they would frisk, run, and chase about, emitting loud squeals and grunts. This was not characteristic of the pigs kept on the other diets mentioned. Furthermore, these pigs would stop and root and devour sand and gravel unless forced to move. This was not characteristic of those receiving Diet 4.

The second time this ration was used was on Lot VI in the fall of 1921. This time five pigs of mixed breeding and averaging 80.8 pounds each were under test. None in this lot developed any indications of the disease. All of them steadily increased in weight from the beginning to the end of the trial, 110 days. Three made an average gain of 107 pounds; one gained 76 pounds; and the other, only 33 pounds. In temperament and disposition these pigs were similar to those in Lot III.

The results obtained with Lot VIII, the third group to receive Diet 4, were not so satisfactory from the standpoint of growth and increase in weight as those in the two previous trials. This group was being fed and cared for at the same time as Lots VII and IX and suffered a cholera "break" also. Five pigs in this lot sickened and died. An examination of the growth curves showed that two of the pigs, 9816 and 9826, only maintained themselves for the 100-day period. Three others made slight increases. There was no evidence of an osteoarthropathy in any of the pigs that finished the trial.

DIET 5

Corn	92 parts
Casein	5 parts
Calcium carbonate	2 parts
Sodium chloride	1 part

This ration combines the supplements of Diets 2 and 4. Corn is the only ingredient carried at a lower level, the others are carried at the same level as when used to supplement the basal ration in their respective diets. Altho a small amount of calcium would be lost in decreasing the amount of corn, it would be compensated for by the amount of calcium combined in the casein.

Lot X, which consisted of five Duroc-Jerseys and a crossbred Poland-China and Chester-White, was fed this ration. The average weight of the six pigs at the beginning of the trial was 110.9 pounds. Hog cholera caused the death of two pigs in this lot. For the first 40 days before their sickness, five were gaining at a rate of .87 pound per day. The sixth pig began to make fair gains but this soon ceased and by the end of the experimental period it had increased only 15 pounds in weight. Two of the pigs maintained an even weight subsequent to the cholera "break." Another lost 15 pounds. None of the pigs in this lot ever showed clinical manifestations of lameness, stiffness, or other symptoms characteristic of the disease.

SUMMARIZED RESULTS OF FEEDING TRIALS

Briefly summarizing the preceding data, it is found that there were 75 swine used in the experiment. Two thirds of them received diets which were more or less deficient in calcium. Of this group 50 per cent developed symptoms of an osteo-arthropathy.

Thirteen of the 24 pigs fed the basal ration showed symptoms of disease. In one, appreciable clinical manifestations were first noted on the thirtieth day. This case marked the shortest time between the beginning of the trial and the appearance of the first symptoms. In another the first symptoms were noted on the thirty-fifth day. Four pigs showed first symptoms between the forty-first and forty-eighth days; two, between the fifty-first and fifty-sixth days; two, between the sixtieth and sixty-ninth days; two, on the seventieth day; and one, on the seventy-second day.

Some of the best average daily gains made by pigs on the basal ration, were made by three in which the disease developed. The rate of gain in five pigs was about the same after the appearance of symptoms as before. The average rate of gain in those pigs was between .25 and .5 pound daily. After the onset of the disease in two pigs, their weight remained nearly constant until the end of the trial. A steady loss in body weight occurred in three pigs after the appearance of first symptoms.

Forty-seven per cent of the swine receiving the protein supplemented ration, Diet 2, showed evidence of a bone and joint disease. The first symptoms were observed in one on the fortieth day, in two on the fiftieth day, and in four on the seventieth day. In the greater number the symptoms appeared between the sixty-first and seventieth days. It was not until the eighty-sixth day that lameness and stiffness were noted in one of the group and in another it was not until the ninety-second day. Three, in which the disease was apparent, rapidly lost in weight from the appearance of the symptoms. The other pigs continued to increase in weight in spite of the disease. Aside from the pigs in Lot IX which suffered a setback from hog cholera, all but one started off at the beginning of the period by making splendid growth and weight increases.

An osteo-arthropathy developed in three, or 42 per cent, of the pigs receiving Diet 3. The earliest case and one of the most severe cases, occurred in this lot. The first symptoms were observed on the twenty-fifth day. The second and third cases developed on the fifty-sixth and sixtieth days. This was more than twice the time for the first.

None of the pigs receiving rations to which calcium carbonate was added at the rate of 2 per cent, developed clinical manifestations of the disease. Twenty-five pigs, distributed among four lots and fed at four different times, received such diets (Diets 4 and 5).

Of the total number of pigs on trial, 45 were males (barrows) and 30 females. Twenty-five of this group developed the disease and of this number 13 were females and 12 males.

SYMPTOMS

The symptoms are principally confined to such as denote abnormalities of the extremities. They vary with the location and the degree of the pathologic process.

In many cases a slight lameness is the only clinical manifestation. In others the symptoms become very marked. Some of the cases become so severe that a complete loss of locomotion is evident (akenesia algera). Such represent the extremes. Many and various intermediate manifestations are encountered.

In the incipient stage of the disease, if one front leg is involved, the particular type of lameness is a supporting leg lameness. In some cases this will subside after moderate exercise. With the progress of the disease, the symptoms become more distinct. When both front legs are involved, a stiff, jerky, and stilty gait is recognized. It is not uncommon to see pigs tumble forward on their faces if made to move faster than a walk, if they are lame in either or both of the front legs. When standing, the front feet are placed farther under the body, causing a marked volar flexion at the carpus (Fig. 3). In others the slope of the pastern is nearly verticle, and the pig appears to be standing on the tips of its toes. In some cases a marked anterior extension of the joint between the first and second phalanges occurs. Puffing or swelling in any of the more distal joints of the legs does not occur. No appreciable changes can be determined by palpation or manipulation of the articulation in the early stages of the disease. Such examinations apparently do not produce pain.

As the disease becomes more advanced the animals are very reluctant to stand. Instead, they will flex the knees and bear their body weight upon them. Many will move about by walking on their knees. Pigs in this condition exhibit much pain when moving from one place to another. Decubitis and necrosis at the pressure points become evident, especially in cases of long duration.

If but one of the pelvic limbs is involved, a combined swinging and supporting leg lameness is usually observed. The affected leg is not carried as far forward as in a normal gait and the feet are quickly placed on the ground. Lameness of one hind leg only is not of frequent occurrence, in cases of long standing. On the other hand, a unilateral stiffness or lameness is usually the first clinical symptom. As a rule both hind legs become involved sooner or later.

When both hind legs are involved the gait is very distinct. The legs are held quite rigid and the stride is short and jerky. The lateral movements of the lumbar and sacral regions are minimized as much as possible because the animal tries to hold these parts rigid.

Pigs in more advanced stages of the disease try to place their hind feet as far forward as possible. This usually results in a "knuckling" or "breaking over" at the pastern joint, and lowers the posterior parts of the body. In some instances, flexion at the tarsus is so marked that the hind cannon slopes downward and forward at an angle of 45° and even more (Fig. 3). In many cases the posterior parts of the body are dropped so that the ischii and plantar surfaces of the pelvic limbs rest upon the ground. When moving from one place to another, the pigs prefer to drag themselves forward by using the front legs as a fulcrum. It is very difficult for a pig to regain its feet from such a position.

A recumbent posture is assumed at all times in those cases which can be classed as very severe. Many assume what may be called a "sidesaddle" position by resting the hind parts on the lateral surface of one thigh, the hind legs being extended to the opposite side. It is exceedingly difficult and often impossible to get a pig in this condition to stand upon its feet, even if manually assisted.

Periarticular thickening of the more proximal joints, shoulder and elbow joints of the front leg, stifle and hock joints of the hind leg, are not unusual findings. In many cases such enlargements may not be observed by visual inspection only, but can be detected by palpation. In a few cases a synovitis with effusion is observed. Thickening of the skin at the pressure points and decubitis often results. Epiphyseal enlargements of long bones were not observed. Appreciable bowing or bending of the bones of the legs was not observed.

It is not uncommon to find fractured long bones or ribs in one or more pigs among a drove where this disease exists. Of the bones of the legs, the femur was fractured most often, and of the ribs, the seventh, eighth, or ninth. Among the experimental animals which could be watched from day to day, lameness was the first symptom. The lameness was observed in either one, two, three, or four legs. In nearly 59 per cent of the cases the first indications of lameness and stiffness occurred in the posterior extremities. About 37 per cent showed first symptoms in the anterior extremities. A small number of cases, 2 per cent, were observed, in which the lameness involved all extremities on the appearance of first symptoms.

Muscular atrophy, especially of the shoulder and thigh, is not uncommon. In many instances this results from disuse, especially if the disease is progressing slowly. On the other hand, cases have been seen in which a marked muscular atrophy occurred soon after the appearance of first symptoms. Twitching of the muscles has been observed in several cases. In some cases a rigidity of the muscles was noted and in others a marked spasticity of the muscles occurred. Reflex sensibilities were not impaired.

Symptoms denoting gastrointestinal and systemic disturbances are not pathognomonic. A partial anorexia usually occurs during the early stages of the disease and unless the diet is changed the pigs seldom return to "full feed."

Excessive rooting, digging, and the eating of earth has frequently been observed. (Specific examples are cited under Diet 4 and in Protocol 6.) This may be considered a sign or symptom. It indicates that the pigs are attempting to obtain something that is lacking in their dietary.

Mortality in this disease is often the result of starvation, because food and water are not so placed that severely affected animals can get it.

PATHOLOGY

The findings at necropsy are usually confined to the joints and bones. Joint and bone lesions of various kinds may occur. The particularly gross changes in some cases involve the osseous structures of the epiphyses of the long bones. Others show periosteal and subperiosteal hypertrophies. Ulceration, erosion, and atrophy of the articular cartilages are not infrequent findings. In many cases the synovial membranes and periarticular structures are the only structures involved. A combination of changes is, however, usually found.

The bones in which the pathological processes are most often observed are those of the limbs. Likewise, the ribs in nearly all cases shows certain abnormalities. At the autopsies of the experimental animals, the bones of the limbs particularly involved and given in the order of their frequency were: the humerus, femur, scapula, radius, tibia, and ulna. The mandible was involved in two cases. No definite changes were noted in the shins or feet, including all bones from the carpus or tarsus to the ground. The same is true of the vertebrae.

It is surprising to find that definite changes which can be noted by gross examination are not commensurate with the clinical manifestations. The converse of this is likewise true, altho it does not seem to occur as frequently.

More than a casual examination of a bone is usually necessary before even quite marked changes can be detected. In other words, to dissect the soft structures free from the bone will not in all cases reveal abnormal conditions. Appreciable gross enlargements of the ends of the bones have not been observed, or bending or curving of the shafts. As a matter of fact, measurements taken from X-ray plates showed that the proximal extremity of the humeri of pigs on low calcium diets, which had developed marked clinical symptoms of an osteo-arthropathy, were not as wide as those receiving the mineral supplement. Occasionally one finds cases in which the humerus, ulna, femur, tibia, fibula, or a rib is fractured or broken, or in which a swelling, callus, or retrogressive change may mark the site of a previous fracture.

Longitudinal sections of the limbs should be made in order to observe certain of the lesions. In extreme cases it is comparatively easy to saw through the bones. The spongy bone in these cases is very soft and its bony spicules in many cases can be crushed and broken with the thumb or finger. The marrow substance is usually white and is of a fatty consistency. In some cases the spongy marrow is very reddish in color, and in others it has a very mottled appearance. Hemorrhages toward the extremities of the shafts of the long bones are often seen. Hemorrhages into the epiphyses of the long bones are seen more often, and they usually are in juxtaposition to the metaphyseal cartilage. The proximal extremity of the humerus and the distal extremity of the femur are the two locations in which such changes are most frequent. Changes in the spongy substance of the short bones such as the carpals, tarsals, phalanges, and also the vertebrae, have not been noted particularly.

Periosteal and subperiosteal hypertrophies are not uncommon. In some cases these are very noticeable while in others they may pass unnoticed. Such hyperplasias can be seen best after the soft tissues are removed and the bone sectioned longitudinally, or with the X-ray. Grossly this lesion appears as an accumulation of a grayish-white tissue which has a rather firm consistency. It can be cut quite easily with a knife and sometimes comes away in crumbly condition. It is not always distributed evenly over the surface of the bone, but may be deposited irregularly.

In three out of five X-ray plates made from severe cases of this disease, periosteal and subperiosteal thickening on the scapula was noted (Fig. 14). The thickened area was situated on the posterior border in two cases and on the anterior in one. A periosteal thickening on the humerus in three of the five cases and on the femur in a like number was also observed. There was no evidence of periosteal lesions on any of the other bones of the legs. In one of our cases, the periosteum was so thickened, that an area on the anterior surface of the femur was seven millimeters thick. In this case the hyperplastic tissue was situated on the outer side of the periosteum as well as beneath it (Fig. 10). A subperiosteal thickening on the posterior aspect of the neck of the humerus and just below the articular cartilage was observed in another case. Most often, however, the thickened periosteal lesion is situated at a point where it appears as an attempt to give additional support or where there is considerable muscle strain.

Only one or two articulations or joints may be affected. One may find changes of a certain form in one joint and a different kind in a second joint. Such findings may occur in the joints of the same leg or of other legs. The joints which showed gross changes most frequently were the shoulder (scapulo-humeral); hip (coxo-femoral); elbow (humero-radial); stifle (femoro-tibial); knee (ulnaro-carpal); and the hock (tibio-tarsal). The most striking changes were observed in the first four mentioned. No gross changes were noted in any of the more distal joints of the legs. In a few instances changes were seen in some of the intervertebral joints, especially in the posterior thoracic and lumbar regions. Enlargements of some of the costo-chondral junctions have been observed in a few cases.

Disarticulation is imperative if nutritional or deficiency disease is expected. In extreme cases well marked pathological changes will be found.

The articular cartilages in a number of cases showed striking abnormalities. In some they appear contracted and thrown into folds or wrinkles, causing deep linear sulci or furrows (Fig. 9). Such lesions when found nearly always involved those articular cartilages having marked convex surfaces. The wrinkling of the surface of the head of the humerus was usually well marked at the periphery. When this wrinkling was evident on condyloid articular surfaces, it was usually in the grooves. At the bottom of the sulci the cartilage was atrophic and necrotic.

Erosive lesions were sometimes found. In some cases marked erosion of the articular cartilage had occurred. Areas of erosion measuring 1.5 centimeters in diameter and extending down to the underlying bone surfaces, were seen in a few instances (Figs. 7, 9). Such lesions occurred most often in the glenoid articular cavity of the scapula. No changes of this kind were found in the acetabulum. Erosions on the head of the humerus were not infrequent. In one case the proximal articular surface of the radius was involved. These areas were not septic. Culture media seeded with material from these areas remained sterile. The lesion is usually dry or nearly so because very scant amounts of synovia are present in such articulations. It was of interest to note that where even several eroded areas were present, there was no evidence of beginning bony ankylosis.

In less severe cases the articular cartilages may show slight depressions, causing an uneven and wavy surface, or the depression may be as little pits. Many cases have been seen where the cartilage is very thin and presents a deep purplish blue color. The cartilage in some instances is softer than normal—a state of chondromalacia.

In nearly all instances where extensive cartilage changes were found, there was also a marked periarticular thickening. The outer layer of the joint capsule is composed of dense connective tissue. It may be a centimeter or more in thickness. The inner or synovial layer may also be thickened. In some cases numerous long villous proliferations from the synovial layer have been observed. They are situated most often along the attached border of the capsule and instead of being diffusely scattered, they occur in more or less isolated clumps. They are often swollen and hemorrhagic. In other cases, however, they cover the entire synovial surface. The amount of synovial fluid is not commensurate with the hypertrophic serosa. Cultures made from these fluids remained sterile.

Lesions in the knee, hock, and the joints of the feet have never been as extensive as in the more proximal ones. As a matter of fact, no appreciable gross changes were noted in the joints of the feet. A thin, purplish-blue and slightly pitted joint surface constituted the most severe lesion in the knee. In only two cases the trochlear articular surface of the tibial tarsal bone showed a slight wavy, uneven, and roughened surface. A thickened joint capsule or periarticular thickening, especially at the knee, was seen more often.

Enlargements at the costochondral junction was observed in some cases. The enlargement in these cases was outstanding and could be recognized readily. The area was firm but could be cut quite easily with a knife.

A simple test which may be employed in an autopsy on a pig, which in a crude way offers an indication of the mineral status of the skeleton, is to force the blade of a knife into the articular surface of some of the long bones. The particular point to note is the degree of resistance encountered in forcing the blade into the bone. In hard bones it is difficult to engage the blade far beneath the articular cartilage, while in soft bones the blade will pass into the epiphysis quite easily. The proximal epiphyses of the humerus and femur and the distal epiphysis of the femur offer the best sites for the application of this test. A second test can be made in connection with the ribs. After the ribs are separated from the sternum, cut the intercostal muscles down to the vertebral column. This frees the rib. Next, grasp the rib firmly with the hands and break it at right angles. A normal rib will crack, splinter, and break through the soft structures. A rib from a mineral deficient pig will bend and break like a piece of cardboard.

Examinations of a great many of the intervertebral articulations, particularly those between the bodies of the vertebrae, have not revealed changes of sufficient importance to relate. On the other hand, deviations from the normal vertebral curves have been observed. The lumbo-dorsal curve was less convex, the lumbo-sacral more convex, and the sacro-coccygeal less convex than in normal swine.

The skin of many of the swine, especially on the ventral part of the abdomen and about the eyes, was thick, dry, and more or less wrinkled. The hair coat was coarse, dry, and lusterless. Decubital sores and especially callosities, were frequently observed. They usually occurred over the pressure points, i.e., knee, fetlock, pastern, and posterior surface of the hock. One usually observes a deformity of one or more of the legs. The thoracic leg may show marked volar flexion at the knee, fetlock, and pastern joints. In the pelvic leg there is anterior flexion at the hock joint, planter flexion at the fetlock and pastern joints. Contractions of the muscles and tendons of the legs often make it difficult and even impossible to extend or straighten the leg. Atrophy of the muscles, especially those of the legs, is not uncommon. Little or no subcutaneous or visceral fat was observed in any of the cases that had been down for from four to seven weeks. The teeth of the lower jaw in three of the cases were loose and the gums appeared very pale. The rami of the mandible in one case was very thick in the lateral diameter. In another, the bones around the nasal cavity appeared bulged. The tonsillar tissue of the soft palate in a few cases was intensely inflamed, and the crypts were filled with caseo-purulent material. In most cases this tissue was not involved.

Significant gross changes in the circulatory, respiratory, digestive, and genito-urinary systems were not observed. No gross changes were noted in any of the nervous tissue. The spinal cords of many were examined but no changes noted. The spinal fluid was cultured in several cases, but in each case the media remained sterile.

HISTOPATHOLOGY

The subperiosteal thickenings are composed mostly of osteoid tissue. The trabeculae are usually wide and are not arranged in a definite manner. In one case where the periosteal lesion involved the shaft of the bone, the osteoid trabeculae were arranged at almost right angles to the vertical plane of the shaft. They were narrow and spaced about an equal distance apart and without much branching. Fine striations running lengthwise with the trabeculae can be seen in many cases.

Areas of osteoid of considerable thickness with small trabeculae radiating from it are often observed. Toward the centers of such areas a group or nest of osteoid cells may be situated. From 3 to 12 or 15 osteoid cells, some large and some small, compose such cell groupings or nests. Many small blood vessels enter the osteoid, especially where it is collected into wide masses. Collections of osteoblasts, 1 to 3 rows deep, were seen along the edges of the trabeculae in various places. It appears that a metaplasia of these cells into the production of osteoid occurs. The spaces between the trabeculae are often filled with fine connective tissue fibers, some osteoblasts, osteoclasts, leucocytes and erythrocytes, marrow cells and fat cells. The fibers are arranged in a dense reticulum. The inner layer of the periosteum in some cases showed a marked increase of fine white and delicate elastic fibers.

The epiphyseal cartilages were often affected. They were wider than normal and very irregular. The cartilage at the periphery of the bone is often wide and becomes much thinner toward the center. In some instances the cartilage spreads out at the periphery in a fan shape. The cells of the cartilage are arranged in columns separated by varying amounts of hyaline matrix. Some columns have two and three rows of cells, others have only one. The cells in the single row columns are usually smaller than those of multiple rows. The cells in the multiple row columns are packed closely together, whereas there is a considerable amount of hyaline matrix between those in the single row. The cartilage tissue along the upper border of the epiphyseal cartilage is usually a more adult type. This border is frequently very irregular. In some instances columns of cartilage cells extended through to its upper border. Many times one would find a very disorderly or hodgepodge arrangement of these cells at the upper border. Some of the columns would bend from a verticle to a horizontal plane. The cells in these columns appeared to be flattened or compressed. Quite frequently small blood vessels could be seen entering the cartilage from the diaphysis and forcing their way between the columns.

There were cases in which the epiphyseal cartilage was much narrower. The columns of cartilage cells in these cases were not numerous. There was a greater amount of hyaline matrix between the columns and little or no proliferative activity was evident.

In a number of instances sections from the spongy bone of the epiphysis and diaphysis showed very thin and calcified spicules. The spaces between them were unusually large. In about an equal number of cases the trabeculae were composed of osteoid tissue. The disposition of the osteoid and its histology was comparable to that described above in connection with the periosteum. The vascular sinuses and blood vessels in many cases were packed with red cells. In most instances osteogenic cellular elements were present in great numbers.

ROENTGENOGRAPHY

Five cases with well marked clinical symptoms were studied with X-ray. The material for photographing by this method was obtained at necropsy. The legs were removed and the skin and most of the muscle carefully dissected away. The entire front leg was removed. The hind leg was disarticulated at the femoro-coxal joint. The pelvis was included with the lumbar, sacral, and coccygeal regions of the axial skeleton. In some instances the material was kept in a 3 per cent formalin solution before the X-ray plates were made. In others it was kept in an ice box.

There was marked evidence of calcium loss in the scapula in only one case. The others indicated only a partial loss. A very striking and outstanding lesion observed in three cases was that of a thickened periosteum. This occurred in the posterior border of the scapula in two cases and on the anterior in one. It was about .6 cm. thick at the widest point and sloped gradually at both ends (Fig. 14). Destruction and absorption of the articular cartilage was well marked in one case and partially in another. Marked calcium loss was not evident in these cases.

All five humeri showed evidence of calcium loss. Here again, one case showed a greater calcium loss than any of the others. It was not the same animal which had shown a greater loss in the scapula. Furthermore, the proximal end of the humerus appeared to suffer a greater calcium loss than the distal end. The proximal metaphyseal cartilage in four cases was completely calcified and appeared as a distinct white line in the X-ray plates. A complete calcification of the distal metaphyseal cartilage was seen in only one case. The distal articular cartilage in the humerus showed evidence of destruction and absorption.

In this case and in one other, a similar finding was observed in the proximal articular cartilage. In two cases rather wide and ill-defined trabeculae extended from the compact bone of the shaft into the marrow cavity which gave the impression that the compact bone was very wide. The compact bone in the case showing marked calcium loss was very thin. A thickened and calcified periosteum was observed in two cases.

The radius in two cases did not appear to suffer a calcium loss. The loss in one case seemed to compare with that of the humerus, while in the others it was less. No definite cartilage changes could be noted.

There appeared to be a greater loss of calcium from the ulna than from the radius in every instance. This is peculiar, because at autopsy the radius seemed to be affected more often than the ulna. A dark undulating line near the proximal end of the olecranon indicated that this cartilage had not become calcified. In four cases a similar line was noted at the distal end of the shaft.

No definite changes were observed in the carpals, metacarpals, or phalanges.

In four of the five cases it was clearly evident that a calcium deficiency existed in the femur. The compact bone of the shaft was very thin in two cases. In one of these a complete fraction at the distal end of the shaft was seen. The shaft in another case was thicker than usual and the posterior border was not concave. Wide trabeculae with rather ill-defined borders were observed. These extended from the compact bone of the shaft into the medullary cavity. The proximal metaphyseal cartilages were more completely calcified than the distal. No pathological changes of the articular cartilages could be determined. A slight thickening of the periosteum was noted in one case.

The tibia in only one case showed a marked calcium loss. The proximal metaphyseal cartilage in this case appeared to be completely calcified. The compact substance of the tibia appeared normal. No bowing or bending of these bones was observed. The distal metaphyseal cartilages in these cases were more completely calcified than the proximal. No definite changes in the articular cartilages could be noted.

The patella, fibula, tarsals, metatarsals, and the phalanges did not show changes.

A few plates were taken of the posterior portions of the axial skeleton. This included the regions of the lumbar, sacral, and coccygeal vertebrae together with the ossa coxorum. Nothing of particular significance could be learned from these plates.

Chart No. 1 expresses in a relative way the calcium status of the bones of normal and of calcium deficient swine. It represents a measure almost proportionate to the density of the bone, i.e., bones deficient in mineral matter are less opaque than those with a greater amount of mineral matter. The degrees of deficiency or calcium loss, i.e., slight, moderate, and severe, represent deviations from the normal. The normal in this case was obtained from the bones of two pigs which had been fed on balanced rations and were normal in so far as could be determined. The results of this tabulation, which represents only a few cases, bring out a point observed at autopsy and when examining the bones by sectioning and breaking. This is, that apparently a condition of halisteresis goes on in some bones more than in others of the same individual. For example in Pig 9800, the humerus shows a severe loss of calcium, the femur and ulna moderate loss, and in the scapula, radius, and tibia only slight loss. Pig 9801 shows severe loss in the scapula, femur, and tibia, with moderate loss in the humerus, ulna, and radius. Pig 9799 shows a slight loss in the ulna, a moderate loss in both scapula and humerus, and a normal condition of the radius, femur, and tibia.

CHART NO. 1

SHOWING CALCIUM LOSS AS PER X-RAY READINGS IN BONES OF SWINE

Pig	Lot	Diet	Bones					
			Scapula	Humerus	Radius	Ulna	Femur	Tibia
9799	VII	1	++	++	N	+	N	N
9801	VII	1	+++	++	++	++	+++	+++
9822	VII	1	+	++	N	N	++	+
9800	IX	2	+	+++	+	++	++	+
9804	IX	2	+	++	+	++	+++	++
9821	VIII	4	N	N	N	N	N	N
9843	VIII	4	N	N	N	N	N	N

NOTE.—N=normal; +=slight; ++=moderate; +++=severe.

PROTOCOLS

A few representative field cases are presented in the following protocols. They show the conditions under which this disease has been observed.

PROTOCOL 1—REDWOOD COUNTY

The owner had 4 Duroc-Jersey sows which he said were "down in the back." They were in very poor physical condition. At the time of our visit in November, and for several weeks prior they had been kept in a small orchard which had been seeded to bluegrass. Their diet consisted of a slop feed of ground oats, kitchen refuse, and water in the morning, and new corn in the evening. In addition, they could have what grass they could get. Each sow was nursing a litter of pigs. One was nursing 7 pigs, one, 4, and two, 5. The litters ranged from

6 to 8 weeks of age and the pigs were in good physical condition and very active. Three of the sows had developed the "down in the back" condition after farrowing and the fourth some time before farrowing.

The following symptoms were observed: temperatures and respirations normal; visible mucous membranes normal; feces and urine voided appeared normal; appetites good. The animals were recumbent and unable to get up on their feet unless manually assisted. When standing marked flexion at the hock and fetlock joint were observed. The posterior parts of the body were thus lowered. Marked flexion at the knee joint was also noted. It was painful for the sows to stand or walk, and the stride was stiff, short, and jerky. They were sensitive to pin pricks. No appreciable swellings, enlargements, or heat was noted over any of the palpable articulations. The sows had not moved a great distance from the places where they were lying. An area about 7 or 8 feet in diameter was rooted and dug up around them, representing the zone of their travels. No autopsies were obtained. There were no other swine on this farm.

PROTOCOL 2—KANDIYOHI COUNTY

Nine in a drove of 30 Duroc-Jersey pigs, between 75 and 125 pounds in weight, were showing typical symptoms of an osteoarthropathy. They were from 5 to 6 months of age and in poor physical condition. They were housed in a dark, unsanitary and poorly ventilated shed but were fed out-of-doors. We visited this farm in March, 1918. Five of the 9 affected swine assumed a semi-sitting posture by extending the pelvic limbs obliquely outward and forward, resting on their thighs. They would propel themselves about with the thoracic limbs and drag the pelvic limbs. No effort was made to stand even if an animal were assisted. Two of the pigs exhibited a spastic paralysis of the hind legs. Atrophy of the extensor and flexor groups of muscles was noticeable. Deformities, such as marked flexion at the carpal and metacarpo-phalangeal articulations were observed in the remaining 4 pigs. Similar deformities at the tibio-tarsal and metatarso-phalangeal articulations were noted in 3. There were no appreciable swellings or enlargements at any of the joints. Examinations of the circulatory, respiratory, digestive, and genito-urinary systems were negative, as far as could be determined. The diet of the pigs consisted chiefly of ear corn, water, and a little skimmilk. A little barley or oats was fed occasionally. No autopsies were obtained. Inquiry revealed that some of the affected pigs had been in this condition for approximately two months. The owner said that he had seen pigs in the same general condition on his farm before, and that, as he remembered, none ever recovered.

PROTOCOL 3—WRIGHT COUNTY

In a drove of 47 swine, 29, or 61 per cent, showed evidence of a bone and joint disease. Almost complete loss of control of the hind legs was readily noted in 18. Most of the pigs assumed a sitting posture with the feet extended to one side. A few extended the hind legs directly backward so that the weight of the hind parts would rest on the dorsal surface of the pelvic limb from a point just below the stifle to the hoof. The hair on these surfaces was rubbed off yet no bruises or injuries of the skin could be observed. The pigs were sensitive to pin pricks. Muscular atrophy of the thigh and leg muscles was noted. No definite joint injury could be determined by clinical examination. Quite remarkable was the way in which these pigs would move about, using the forelegs to drag or pull themselves forward. Four of the affected pigs could not move from their places. These pigs could not stand up on their feet unless given manual assistance, and this caused much pain. The anterior members alone were involved in some cases. The pigs would move about by walking on their knees and fixing or immobilizing the shoulder joint. Some were very stiff and jerky in their movements. This drove of pigs was between 6 and 7 months of age. They averaged about 120 pounds in weight, and were of mixed breeding. The owner was very much discouraged. He had expected that by that time they would have been about 100 pounds heavier. The disease in some of the pigs had been in progress for as long as 3 months. Others were becoming affected from time to time. Their ration consisted of equal parts ground oats and barley made into a slop with water and fed in the morning. In the evening they received shelled yellow corn. The housing facilities were fair. They had the run of a wooded pasture but the foraging was poor at this time of the year, April. No deaths were reported and no autopsies obtained.

PROTOCOL 4—FREEBORN COUNTY

Eleven pigs on a farm all showed definite clinical symptoms of an osteo-arthropathy. They were Duroc-Jerseys, about 6 months of age and about 100 pounds in weight. The environment was conducive to a mineral deficiency disease. The house and pen in which the animals were kept had a solid plank floor. The pen was about 12 feet square and out-of-doors. No other runway and no pasture were available. Ground oats and barley were the principal feeds. Some nubbins of soft silage corn were thrown into the pen for a few days while the silo was being filled. The pigs could not walk. They would move about by using the front legs as a fulcrum, dragging the hind parts forward. Marked flexion at the joints was evident. Manipulations of the shoulder, elbow, stifle, and hock joints caused them much pain.

No appreciable enlargement of these joints was noted. A "wanting" expression of the face was clearly recognizable. No other symptoms were noted. Three weeks had passed since the owner had noticed the first signs of the disease. That the pigs were in great need of mineral matter was stressed. Bone meal and a teaspoonful of cod liver oil for each pig every day, were prescribed. The owner said that he had raised pigs in the same way and in the same place for thirty years and never before noticed such conditions. It was learned later that he did not follow the suggestions as to the use of bone meal and cod liver oil, but disposed of the pigs.

PROTOCOL 5—FREEBORN COUNTY

Five in a drove of 60 spring pigs showed characteristic symptoms of a bone and joint disease. The pigs had the run of a barn yard and an adjoining orchard. Their diet consisted of a slop feed of ground oats and barley mixed with skimmilk and of ear corn scattered on the ground. Four of them could get about fairly well, but the fifth could not. The first pig's symptoms had appeared about a month or five weeks previous. The owner said that because they could not "keep up" with the rest he separated them from the drove, allowing them the run of the farmstead. At the time of our visit these pigs were still running about the farmstead and did not show evidence of disease. A careful inspection disclosed the fact that near the farm house was a pile of old plaster and a mortar box. The owner said he had noticed the pigs eating this material. This indicated that lime was one of the elements lacking in their diet and it was suggested that he supply all the pigs with this material. At a later date it was learned that he had complied with this suggestion and that no new cases developed.

Eight other farms in the immediate vicinity were visited and from 15 to 65 per cent of the pigs were similarly affected. The local veterinarian knew of still other farms in the vicinity where this disease existed.

PROTOCOL 6—WASECA COUNTY

A disease of swine reported to be quite extensive in this section of the state, was investigated in August, 1922. The first drove visited consisted of 180 head of purebred Chester-Whites, between the ages of 4 months and 3 years. About 130 were farrowed in the spring of 1922. Sixty-nine showed evidence of an osteo-arthropathy. A good clinical picture of almost any stage or degree of the disease could be observed. The oldest cases had shown symptoms for less than a month and the pigs affected were between 5 and 6 months of age. Only three of this group were able to move about without much difficulty. A number exhibited marked symptoms of lameness, the stride being short, stiff, and jerky. The lameness was apparent in one front leg in some cases; in both front legs in others. In some, one hind leg was involved; in others, both hind legs. Others were lame in both front legs and one hind leg, or both hind legs and one front, or in all four legs. Autopsies of two of the most severe cases revealed extensive arthritic and osseous changes. The joints particularly involved were the shoulder, elbow, and stifle joints. The articular cartilages were thin, uneven, and wavy or wrinkled, especially those of the head of the humerus and the condyles of the femur. The synovial membranes were thickened and villous-like proliferations extended into the cavity. Some periarticular thickening was apparent. The long bones, humerus, and femur would break very easily. The ribs would also bend and break easily. No gross changes were noted in any of the thoracic or abdominal viscera.

These pigs had been fed on ground oats and corn, shorts, and cooked barley, mixed into a slop with skimmilk or buttermilk. In addition they had access to alfalfa and rape pasture. The pasture was large enough and they had plenty of green forage. It was noted that throughout the pasture there were areas where the soil had been rooted or dug up by the pigs. As further proof of this the faces of the pigs were literally covered with dirt. The owner was contemplating "ringing" in order to prevent rooting. Houses, sheds, pens, troughs, and feeding floors were exceptionally well constructed and kept in good condition and clean.

A diagnosis of a calcium deficiency disease was made, and the owner was advised to supply calcium. Calcium carbonate in the form of air-slaked lime, dried and powdered, was added to the ration at the rate of 5 pounds to each 100 pounds of feed. A report received the following January said that shortly after the treatment was begun, all but three of the affected pigs made excellent recoveries and no new cases developed.

A next neighbor with 44 purebred Chester-Whites, 13 spring pigs, showed well marked clinical symptoms of the same disease. His swine were kept under practically the same conditions. The same treatment was advised and the results were just as satisfactory.

PROTOCOL 7—WASECA COUNTY

There were about 250 purebred Duroc-Jersey swine in this drove, of which nearly 200 were spring farrowed. There were no clinical cases of an osteo-arthropathy among any of the swine at the time of the visit and the owner said he never had had a hog which showed symptoms such as we described. Inquiry revealed that the diet of these swine consisted essentially of the same foodstuffs as those referred to in the preceding protocol, with the addition of ground bone.

The pigs ate considerable amounts of this material. An interesting and striking observation was that the pastures were not rooted or dug up by the pigs and none of the animals wore rings. A report from this farm the following January showed that no cases ever developed.

PROTOCOL 8—LINCOLN COUNTY

This drove of swine seen in May consisted of approximately 300 head of Poland-Chinas. Some were purebred, others grades. Thirty were winter farrowed (in November and December). Nearly 60 per cent of these showed symptoms of a bone and joint disease. The owner said some of them were "weak in the legs" before weaning. He attributed this to the unfavorable season for farrowing, saying that the sows were poor "milkers" and that the pigs were usually small when born. Seven yearling gilts also showed symptoms of stiffness and lameness. When forced to get up they would walk a short distance and lie down again. These gilts had all nursed litters earlier in the spring. The owner was feeding his entire herd of 300, a mixture of corn, oats, and barley, self-fed in three large hoppers and tankage from a separate hopper. A sufficient supply of water apparently was provided. No special provisions were made to take care of the crippled pigs. No autopsies were obtained. The owner was advised to supply a liberal amount of bone meal and keep it before the pigs at all times. Better pasture facilities were also suggested. This he agreed to. No further word was ever received from him.

PROTOCOL 9—DAKOTA COUNTY

Eighteen fall gilts with well marked cases of a mineral deficiency disease were found on this farm. Akinesia algera was evident in most of them and it involved all four legs. Some of the pigs were able to move about, but with much pain. The humeri in two pigs were fractured, and the tibia and fibula in a third. The fractures we believe were the result of rough handling on the part of the caretakers. A disease of this kind lends itself to such injuries quite readily. It was learned that most of these pigs had shown symptoms for as long as two months. None of those affected improved and none died. A post-mortem on two of the affected pigs revealed marked arthritic and osseous changes. The skin and hair coats were harsh, coarse, and rough. The body was emaciated. The muscles of the legs were atrophied, firm, and dark in color. There was a periarticular fibrous thickening about the shoulder joint. The synovial membrane was hemorrhagic and thickened, especially that part attached to the humerus. The articular cartilages were uneven and wrinkled, and some erosive changes were observed. The articular cartilage of the elbow joint was also wrinkled and very thin, especially over the contact parts. One could force the knife into the ends of the long bones very easily, and the bones were easy to saw through. The frontal bones of one of the pigs seemed to be thicker than normal. No gross lesions were found in the thoracic or abdominal organs.

Besides the 18 affected pigs there were 52 pigs of approximately the same age. There was no evidence of disease in these pigs. All pigs on this place were purebred Hampshires. Their diet consisted mainly of soaked corn, oats, and barley, much of which had been scorched and burned in an elevator fire. A small amount of semi-solid buttermilk was also fed. Pasture was not available. Calcium carbonate was suggested as a mineral constituent which was to be supplied regularly. The suggestion was carried out and the owner later informed us that seven pigs made suitable recoveries or were at least marketable, and no new cases developed.

PROTOCOL 10—ROCK COUNTY

Eleven in a drove of 78 grade and crossbred swine were in such a crippled condition that it was almost impossible for them to move about. They were housed in a straw shed with a board floor and had the runway of a barnyard where a few thin milk cows and several horses were kept. Ground corn, red dog flour, oil meal, and a commercial stock food were mixed into a slop and fed to them in the morning. Yellow ear corn was scattered on the ground at the evening feeding. All affected pigs were born the previous October and were 6 months of age. The first signs of stiffness or lameness had been observed about 6 weeks before. As the owner put it, "first one, then another, then another, etc., developed the disease." The symptoms and post-mortem findings were similar to those already described. Disposal of the most severely affected pigs was advised, and bone meal and cod liver oil were prescribed for those to be kept. A report was received from this man about 4 months later expressing his satisfaction with the results obtained.

PROTOCOL 11—RAMSEY AND HENNEPIN COUNTIES

This protocol covers conditions found on a group of farms where the principal foodstuff of the swine consisted of garbage. Knowledge concerning the conditions on these farms was based on several years' acquaintance. On some of the places only about 50 head of swine are kept; on others as many as 500. As a general rule the swine are kept under "dry lot" conditions, pastures being available on only a few farms. The facilities for feeding and housing ranged from very good to very poor. Some feeders "finished off" their swine on cereal grains, others never fed anything but garbage. It is the practice on some of the places to purchase feeder pigs (pigs weighing from 60 to 110 pounds) and feed them out, while others raise their own. We have never seen or heard of a disease characteristic of an osteo-arthropathy on any of these farms. This is not surprising when one considers the variety of foodstuffs represented in garbage. It should carry some of all of the elements necessary in nutrition.

DISCUSSION

In literature on hog-raising, one can find descriptions of and references to a disease in many respects similar to that described. The agreement of these reports has to do chiefly with the clinical manifestations or symptoms. The morbid anatomy, both gross and microscopic, tho not agreeing in all points, nevertheless shows that certain bone changes are more or less alike. The differences are mostly those which indicate osteoporotic changes as one extreme and rachitic changes as the other. However, an admixture of changes characterizing both osteoporosis and rickets are more often observed. The pathology of diseases of this nature is not specific. It is, however, receiving much study at the present time.

Rather close agreement is found as to etiology. We refer to the fact that the disease is one of trophic rather than of microbian origin. The specific nutritive elements concerned and their relation to one another as causative agencies, are matters upon which there are differences of opinion.

Goldberg, Maynard, Williams, and Christy (5) stress the importance of the addition of cod liver oil or alfalfa hay to the ration as factors favoring the prevention and cure of swine affected by "posterior paralysis." In one experiment their basal ration consisted of yellow hominy, 200 parts; standard wheat middlings, 100 parts; casein 4.5 parts, mixed into a slop with an equal weight of skimmilk, raw in some instances, pasteurized in others. Pigs fed this ration became stiff and lame. When the condition had progressed to a point which it was thought characterized the disease (posterior paralysis), some were destroyed for examination, others used to test a cure. One was cured by adding cod liver oil to the ration. A more interesting result was the fact that similar clinical and pathological changes were observed in pigs receiving as a supplement to the basal ration, a mineral mixture (equal parts of calcium carbonate and bone meal) equivalent to 2.5 per cent of the ration. Two of the affected pigs in this group were restored to health after adding alfalfa hay to the ration.

In another experiment a group of nine pigs was fed a ration composed of yellow hominy, cottonseed meal, middlings, molasses, calcium carbonate, and bone phosphorus. Within two months all were stiff. Four were killed and examined. They showed definite bone changes. The remaining pigs for five days received in addition to their regular diet, 30 spoonfuls of tomato juice. After this period alfalfa hay at the rate of .5 per cent of the ration was fed. This line of treatment was not begun until all the pigs were in the very late stages of the disease. Within two months from the beginning of the treatment the pigs returned to normal condition. Minerals were fed *ad libitum* it is said, "but the pigs appeared to have made marked improvement before these minerals were consumed at all."

In a study of the factors responsible for rickets or partial paralysis in swine, Bohstedt, Bethke, Edgington, and Robinson (6) in Ohio, fed a large group of pigs, ground white corn, wheat flour middlings, linseed meal, blood meal, and salt as the basal ration. This was supplemented with minerals (calcium carbonate, disodium phosphate, and precipitated bone flour), protein (casein) and Vitamin A (cod liver oil, whole and aerated). These supplements were fed alone with the basal ration or in combination. The experiment included 10 lots of 8 pigs each, and continued for a period of 160 days.

Their report shows that 31¼ per cent of the pigs died. The experimenters say that death was "due to rickets, respiratory trouble, or the effects of deficient rations generally." In all but one case the deaths occurred in the lots not receiving additional vitamins. Lameness was not observed in any of the pigs which received cod liver oil. One case occurred in each lot receiving mineral or protein supplements. Three cases developed in the lot receiving only the basal ration.

The results of the experimental feeding trials at the Minnesota Station indicate that calcium is a very significant factor in connection with the etiology of the disease here reported.

Rations low in calcium but carrying a good supply of Vitamin A were fed to 50 head of swine. Of this number, 25, or 50 per cent, developed a clinical syndrome characteristic of a bone and joint disease. A difference in the degree of severity of the symptom complex was observed in the affected pigs. The earliest indication of disease occurred on the twenty-fifth day in one case. In another case the first symptoms were not noted until the ninety-second day. Symptoms in the other cases appeared between these two extremes.

When it is remembered that the average weight of the pigs at the beginning of the feeding trial was 87.22 pounds per head and that the age varied between 4 and 6 months, then 50 per cent of "takes" is a large number. It might reasonably be thought that if the pigs had been younger and less mature, a greater number of cases would have developed. Under field conditions, the disease was found to occur most often in pigs weighing between 60 and 125 pounds. More of the pigs weighed nearer the former figure than the latter. In some instances pigs weighing about 30 pounds showed typical symptoms of the disease. Heavier swine were also affected.

Another significant fact pointing to the rôle calcium plays in relation to this disease, is that none of the pigs receiving calcium carbonate, equal to 2 per cent of the ration, developed an osteo-arthropathy. In all there were 25 pigs which received this supplement. In this connection attention is again called to Protocols 6 and 7. These offer a striking example, showing the results of the use of an additional mineral supplement in the dietary. Other similar cases could be cited.

Elliot, Crichton, and Orr (7) reporting upon some of their work in connection with "Rickets in Pigs" obtained results similar to those of the Minnesota Station. They fed various diets to several lots of swine. One of the rations was exceptionally low in inorganic matter but carried an abundance of the Vitamins A, B, and C. Within 60 days from the beginning of the trial the pigs showed marked evidence of malnutrition. They moved about with very stiff and stilty strides. Another group which received the same ration plus inorganic matter, consisting chiefly of calcium salts, did not show such symptoms. The pigs of this group grew and increased in weight at a rate which was 50 per cent better than those in the first lot.

A ration which was poor in both protein and minerals constituted the basal ration of the same experimenters in a second trial. One lot of four pigs received this ration. For a second lot protein only was supplemented. A mineral mixture plus the basal diet was fed to a third group, and a fourth group received both protein and mineral matter. The results were quite striking. No manifestation of disease (rickets) was observed in the pigs receiving the salt mixture as part of their diet. On the other hand rickets developed in those not receiving the salt mixture.

Reports of investigations of nutritional studies or feeding trials with swine, often contain sections or paragraphs describing certain clinical manifestations or disease. Stiffness of gait, lameness, or paralysis are the phenomena which particularly characterize the disease. Many of the reports contain nothing more than a record of such symptoms. Others describe in a little more detail certain factors in the disease. In this connection some of the early work of Hart, McCollum, and Fuller (8) is of interest. One of the rations they were feeding a group of swine, carried phosphorus at a very low level. In fact, it supplied only 1.12 grams of phosphorus per pig per day. It consisted of rice, wheat gluten, and bran, plus a mixture of sugar, sodium chloride, magnesium chloride, and potassium sulphate.

One pig receiving this diet showed the first signs of stiffness on the thirty-third day. The stiffness occurred in the hind legs and resulted in partial loss of control. Within a few days the two other animals of the lot showed similar symptoms. The symptoms became more severe, and later the pigs were totally disabled and could not move about. The authors state that "when standing, the hind limbs assumed an oblique position, the hind feet resting far beneath the body and near the fore feet. One animal in this lot entirely lost the power of sustaining its hind quarters." Similar syndrome occurred in a second lot of pigs which were fed the same ration, but at a later date. A small outside pen (free from vegetation) was provided for the latter group. This afforded opportunity for exercise, a point which the authors thought might have been a factor in connection with the development of the stiffness.

Gross examinations of some of the long bones from these animals showed that they were of a looser texture than those from normal swine. They were more spongy and their breaking strengths were lessened. The writers note that the bones indicated severe osteoporosis. Bones from swine fed a ration carrying sufficient amounts of calcium phosphate did not show such characteristics. Neither did the latter show any of the clinical symptoms described.

Another very interesting example of a paretic-like disease of swine was observed in connection with certain feeding experiments at the experimental farms, Agassiz, Canada. A large number of pigs were fed rice meal to compare its feeding value with that of more standard condiments. Rice meal, skimmilk, and mangels constituted the basal ration in these trials. This was supplemented with wheat shorts, oats, barley, peas, ground alfalfa, potatoes, and dried blood, in various combinations. P. H. Moore (9) when reporting the results of these trials, emphasizes the fact that in every instance in which rice meal was fed as a part of the diet, the hair coats of the pigs became rough and that later, symptoms of stiffness and lameness were evident. The first signs of stiffness occurred as a rule about the fiftieth day. Two pigs, however, showed such symptoms at about the thirtieth day. None of the pigs receiving diets in which no rice meal was used ever showed signs of stiffness, lameness, or roughened hair coats.

Hadwen (10) reporting upon these pigs from the standpoint of a clinician and pathologist, notes that a painful lameness developing very suddenly and a wild staring expression of the face are characteristic symptoms. In reference to this he says: "A pig that had been quite active in the evening would be lame the following morning,"—with a "wild staring facial expression with the eyes nearly popping from the sockets." The character of the lameness or of the posture assumed when standing or walking is not described in detail. From the attitude assumed by affected pigs (deductions of the writer from photographic plates), it would appear that the animals were endeavoring to fix the position of the legs when in a standing position and then allow the axial skeleton to decline backward and downward. The front feet are placed farther forward than normally as are also the posterior feet. The lowered sacrum results in a marked flexion at the hock and fetlock joints, and thus the long axis of the metatarsus approaches a horizontal more nearly than a vertical plane. Hadwen also speaks of heart attacks as a frequent symptom in many of the affected swine. These were characterized by heavy breathing for a short period followed by loss of breath, and a stiffening out as if the animals were going to die. Such attacks were of short duration. They occurred in some pigs as many as two or three times in a single day. Some of the affected pigs were killed. A post-mortem showed no changes in any of the viscera. The bones were very soft and could be cut easily with a knife. No further descriptions were included. Since an osteogenic weakness was the particular manifestation and since it was known that rice meal is deficient in phosphorus, the idea was put forth that therein was a possible explanation for the disease. The idea that rice meal contained substances of a toxic nature was largely abandoned.

In the light of present knowledge, these deductions were largely correct. In fact, many experiments with laboratory animals, also with some of the larger animals, show that a disease manifested by marked osseous changes can be induced by feeding diets low in phosphorus. Phosphorus combined with calcium and magnesium forms about 86.5 per cent of the inorganic materials of the bones, calcium phosphate representing 85 per cent and magnesium phosphate 1.5 per cent. The relation of calcium to phosphoric acid in bone, according to Mathews (11) is 10 Ca : 6 PO_4. This denotes the importance of phosphorus as a mineral constituent of bone.

The results of Moore's (9) experiments add much ground for belief in the inorganic deficiency of the ration as a causative factor in the bone and joint disease described in this paper. The rations Moore fed carried phosphorus at a lower level than do most swine diets. It is regretted that a more detailed description of the pathology of their cases was not included. However, it was clearly recognized that a condition which presented abnormal osseous changes was being dealt with.

Wehrbein (12) in 1916 described a disease of swine characterized by paralysis, which he said was becoming more and more frequent among pigs in Iowa. The fact that the symptoms presented by affected pigs were such as might characterize paresis, caused him to direct his investigations towards the nervous tissue. The work was confined principally to the examination of the sciatic and axillary nerve trunks. Nerves from the axillary region were examined from cases in which paralysis occurred in the front legs. The lesion observed was characteristic of degeneration, which gave rise to the designation "Polyneuritis parenchymatosa."

We have examined microscopically, sections from the axillary, radial, ulnar, femoral, muscular branches of the sciatic and tibial nerves from five of the pigs used in our experiments and from some field cases, and have found changes identical with those described by Wehrbein. In one of our cases, Pig 9889, Diet 1, Lot XI, with complete cessation of locomotion, it was interesting to note that not all of the fasciculi in a nerve trunk showed evidences of degeneration. A section from the femoral nerve showed a group of fasciculi which appeared normal, then another group in which some degenerated fibers occurred, another group in which more fibers were degenerated, and still others in which nearly all of the fibers were involved. In another case, Pig 9757, Diet 3, Lot IV, a pig which had shown definite symptoms of an osteo-arthropathy, but in which the symptoms had not become severe, a section from the axillary nerve showed some degenerating fibers in all of the fasciculi. The section from the tibial nerve in this case showed many normal fasciculi and some in which the fibers were degenerating. These neurologic changes we believe to be the result of a suspension of functional activity and not a primary lesion. It should also be stated that in the cases just mentioned, there was macroscopic evidence of muscular atrophy, i.e., in the muscles of the limbs.

Wehrbein points out that nothing of importance was revealed by gross examinations of the viscera. The spinal cord, nerves and their coverings did not show gross changes. And further he says "Careful examinations of the bones were made, as we had reason to believe that the disease in question is related to rickets, but without result." The coxo-femoral joint was examined. The teres ligament was swollen at its proximal insertion in some cases. The joint cavity was often filled with blood. Such changes, however, were observed in normal swine which had been handled roughly before killing. He mentions the fact that both rachitis and "paralysis" have been observed in the same animal and that it is often difficult to differentiate between the two macroscopically. The symptoms he describes are very similar to those we have observed and are presented elsewhere in this paper. He reports that the disease usually occurred in pigs less than six months of age and usually from the same litter, tho sows showing definite paralytic symptoms were observed. This occurred after parturition in the sows and was believed to be a disease different from that reported.

Our observations coincide with Wehrbein's in so far as the disease was observed in younger swine more often; that is, in pigs from six to seven months of age or less. We have further observed that the disease existed more often among pigs born in the fall and then pen fed through the winter than in pigs farrowed in the spring or the early summer. Accurate records were not available, so that we could determine the genetic relationship between affected or nonaffected pigs in the droves investigated, but we are of the opinion that familiar heritance does not exist. Familiar susceptibility, on the other hand, may, and possibly does, exist, not by any genetic influences but through environmental trophic conditions. It is not uncommon to find nursing sows exhibiting typical symptoms of an osteo-arthropathy without any of the offspring being affected. In a statement concerning the cause of "polyneuritis parenchymatosa" Wehrbein points out that infections and food intoxications can be safely disregarded but attributes the disease largely to hereditary dispositions and tendencies.

At Cornell University, Maynard, Goldberg, and Miller (13) have been investigating a disease in swine which they designate as "stiffness." Their report covers four trials, in which they used 95 pigs. Thirty-two per cent of the pigs receiving rations particularly low in calcium developed "stiffness." This is 18 per cent less than the number developing a similar condition in the experiments conducted at the Minnesota Station. The ration used at this station, however, was even more restricted in the amount of calcium supplied. Another interesting point of difference between the results obtained at the Minnesota Station and those at Cornell is the fact that none of the pigs receiving rations to which calcium was added at the former institution, developed clinical manifestations, such as showing evidence of stiffness or lameness; while 13 per cent of those receiving rations having an "ample" supply of calcium did show evidence of stiffness in the Cornell trials. In partial explanation (Maynard, et al.) note that the trial was conducted in the winter months when the pigs were stabled. Full benefit of sunshine was not therefore afforded. Also note that a correlation on an ancestral basis existed between the pigs which developed the stiffness and the fact that they were born from sows which varied in bone condition and vigor. These men believe that the trouble (stiffness) is not caused by a mere lack of calcium but that adequate mineral nutrition depends upon assimilation as well. That assimilation is enhanced was brought out by the fact that when some of the pigs which developed stiffness on diets supplying minerals were given 10 cubic centimeters of cod liver oil daily, they soon showed improvement and some returned to normal.

The results obtained by these workers in regard to the production of the disease and with its prevention, agree favorably with the results obtained in these laboratories. That the lesions are principally confined to the long bones, together with lesions at their articulations, is another point of similarity. An extensive study of the microscopic changes in the affected bones was made by them with the result that they too found various pathological manifestations, some which were characteristic of those described for rickets in small animals; others which might be osteoporotic and in some changes somewhat characteristic of scurvy.

CONCLUSIONS

1. There occurs in swine a disease of the bones and joints—an osteo-arthropathy.

2. This disease belongs to the group of trophic diseases. It is a deficiency disease.

3. A lack of calcium is closely associated, or may be the limiting factor, in the rôle as the causative agent. Swine fed rations which supplied calcium at a low level developed typical cases of bone and joint disease.

4. Calcium carbonate (lime, slaked, dried, and then pulverized) when added to the ration at the rate of 2 per cent, apparently supplied the deficiency. None of the pigs receiving it developed the disease.

5. Stiffness, lameness, and later loss of function are characteristic symptoms of the disease. The stiffness and lameness may occur in but one, two, three, or in all four legs.

6. The typical pathologic changes occur principally in the long bones and in the articulations between them. The degree or extent of the morbid change may not be uniform in all the bones of the limbs or in any single bone. This also applies to the articulations. Thus it is imperative that all the diarthrodial joints of the limbs, beginning with the knee and hock and including those proximal to them, should be inspected when examining a patient or cadaver.

7. Because of the irregularity of the histologic changes in the bones we have studied, it was not considered advisable to adopt a specific nomenclature. In some cases the lesion was quite typical of rickets; in others of osteomalacia, and in some of atrophy. There were others that showed changes suggestive of an admixture of rickets, osteomalacia, and atrophy. For these reasons and such as have been mentioned before we are calling attention to a disease of the bones and joints—an osteo-arthropathy—of swine.

ACKNOWLEDGEMENT

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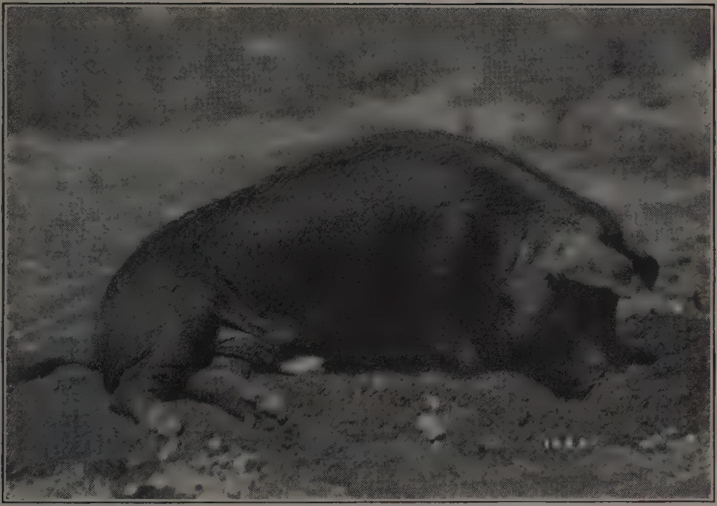

Fig. 1. Pig 9769

This shows a stage of the disease in which there is loss of motor function (akinesia algera). Note how the pig has rooted and torn up the soil, indicating that it is trying to get something from the soil to satisfy a deficiency in its food supply.

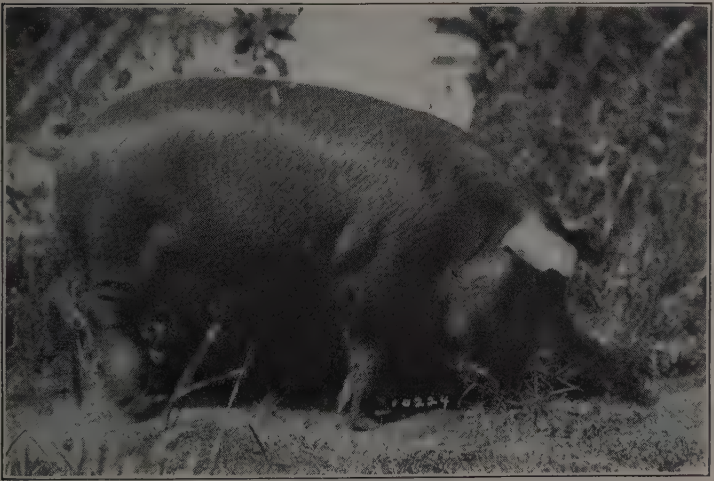

Fig. 2. Pig 9779

This figure shows an early stage of the disease in which the anterior limbs are involved. Note the volar flexion at the right carpus and the slope of the phalanges and also the slight atrophy of the muscles in the region of the arm.

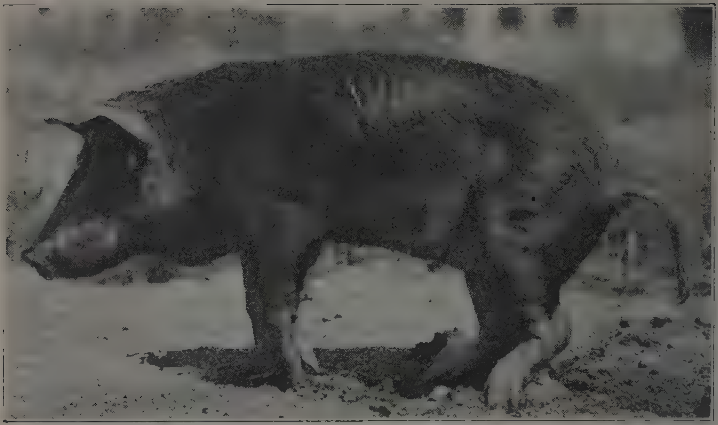

Fig. 3. Pig 9889

This represents a characteristic standing position of many pigs affected with an osteoarthropathy. The feet are placed farther under the body, the hind parts lowered, and there is marked flexion at the hock joint and the knee joint.

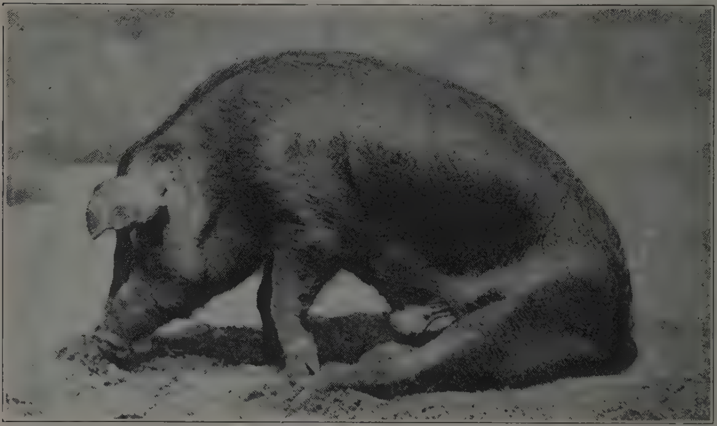

Fig. 4. Pig. 9837

This is typical of a position often assumed by pigs affected with a bone and joint disease. The hind legs are extended forward and outward.

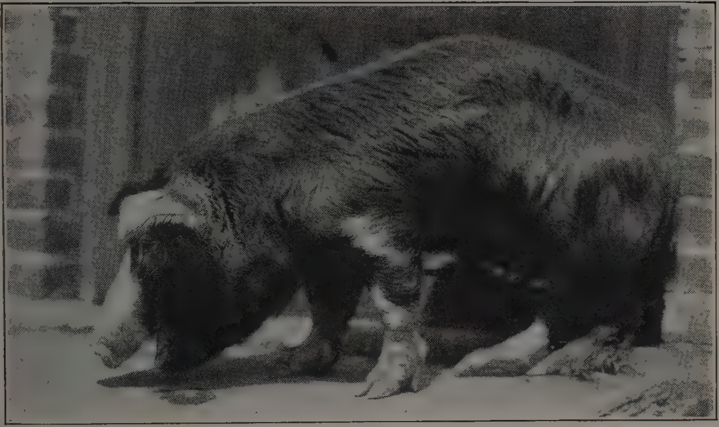

Fig. 5. Representing a Clinical Picture Typical of Rickets

Note the enlargements of the facial bones, the bowing or bent radius, and the position of the hind feet. The spinal column shows marked lordosis. This animal was brought to the laboratory for diagnosis. Compare with Figure 2.

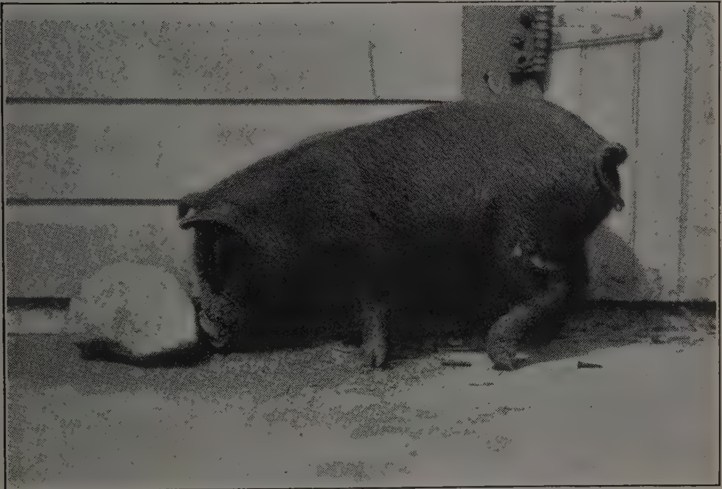

Fig. 6. Small Pig, 25 Pounds in Weight

The pig is nearly four months old and shows typical symptoms of a bone and joint disease.

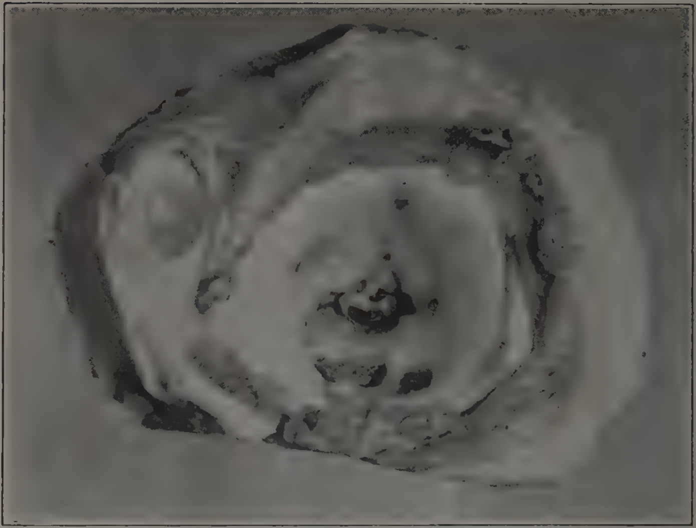

Fig. 7. Articular Surface of the Scapula, Pig 9781

This shows very clearly the extensive erosions, depressions, and pits in the articular cartilage, the thickened synovial layer of the capsule with its swollen villi, and the thick fibrous periarticular tissue.

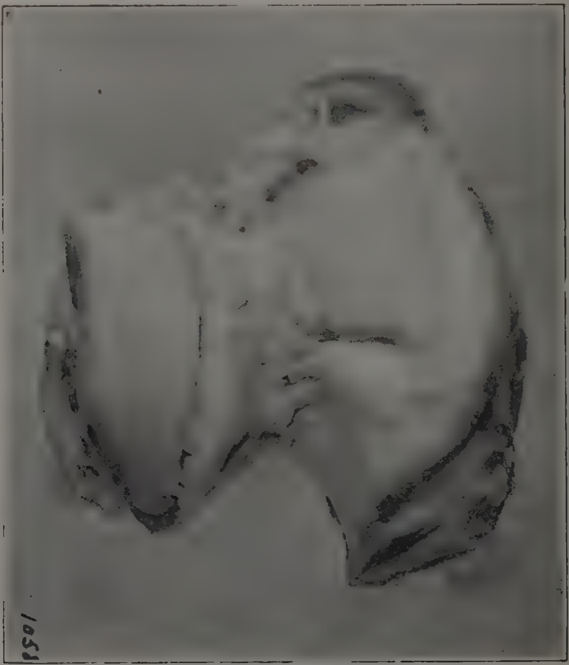

Fig. 8. Distal Extremity of Humerus, Pig 9781

The surface of the cartilage is very uneven and wrinkled, especially in the sagittal groove of the medial condyle. The lateral condyle is normal.

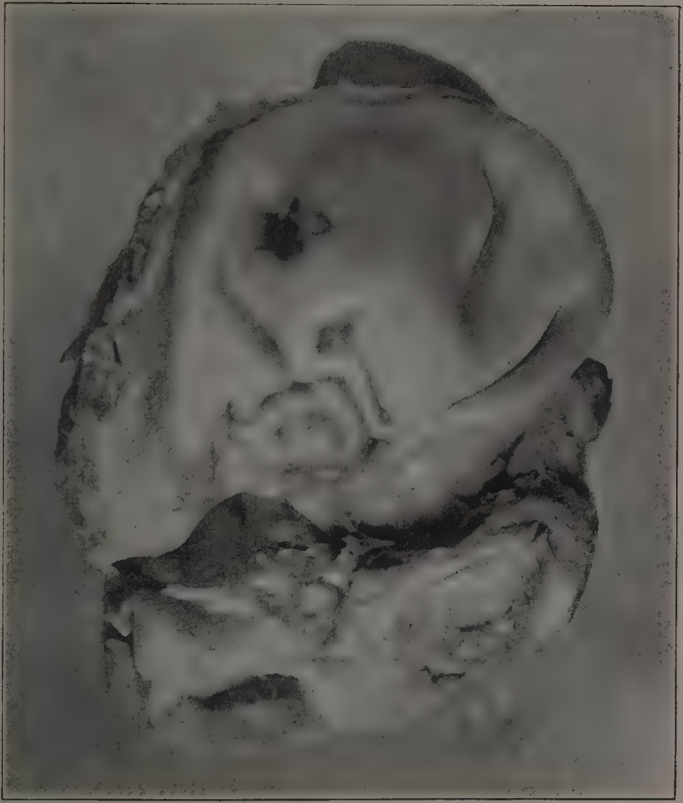

Fig. 9. Proximal Extremity of the Humerus, Pig 9889

Marked wrinkling and crevices in the cartilage are very distinct. The cartilage was very uneven and rough and a deep erosive lesion is apparent.

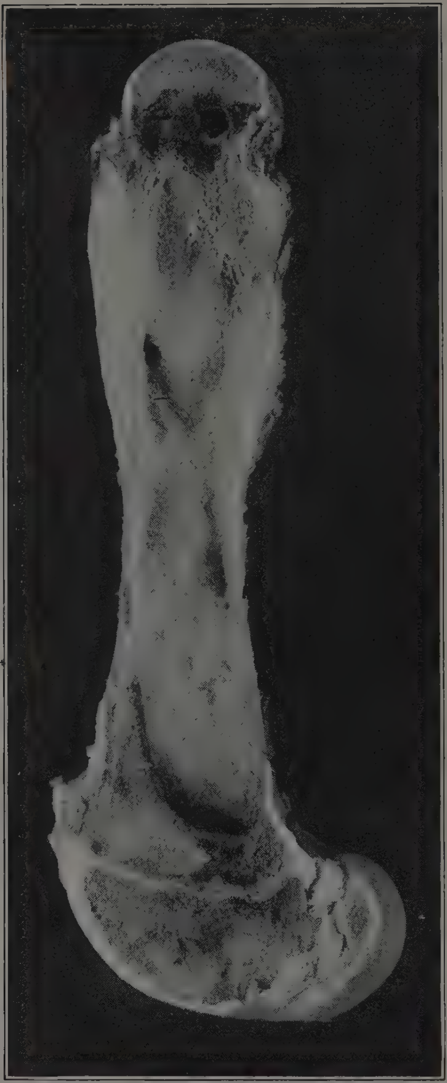

Fig. 10. Longitudinal Section of the Left Femur, Pig 9765

This shows the marked periosteal and subperiosteal thickening at the proximal third of the shaft. This is mostly osteoid tissue. The compact substance of the shaft in this region is very thin. There is an increased amount of fibrous periosteal tissue as shown by the white line. Cavernous hemorrhagic and cryst-like formations can be seen at the proximal metaphysis.

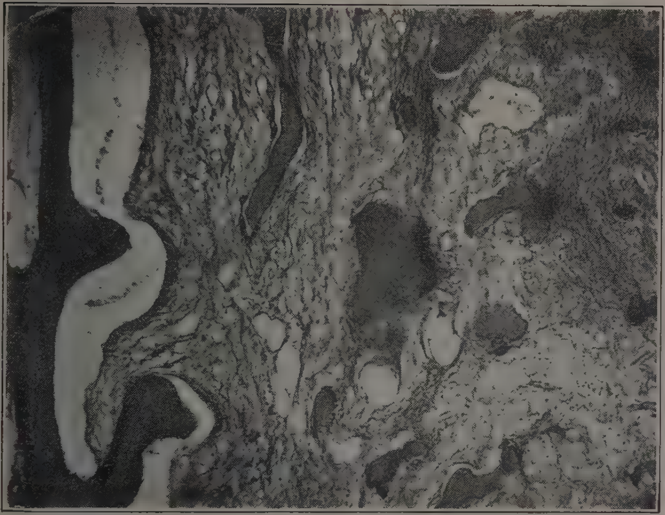

Fig. 11. Section of Shaft of Femur, Pig 9765 (Photomicrograph)

Irregular areas of osteoid and a few bony spicules, between which are a great number of undifferentiated fibroblasts and much fibrin.

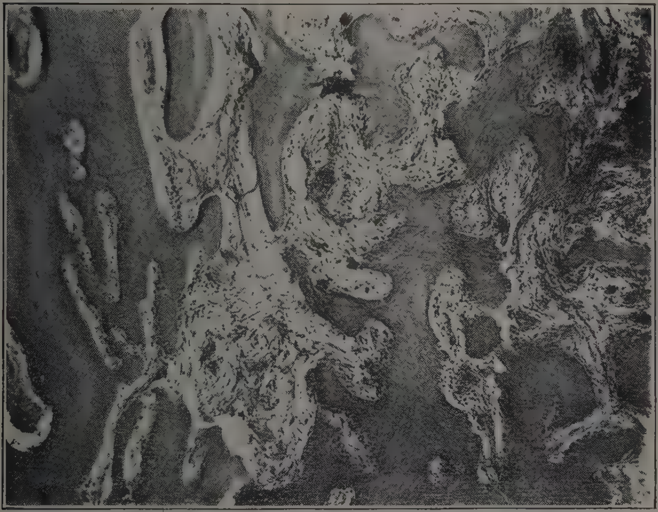

Fig. 12. Section from the Periosteal Thickening, Pig 9765 (Photomicrograph)

This shows the wide osteoid trabeculae in which groups or nests of osteoid cells occur. A few osteoblasts are situated about some of the trabeculae.

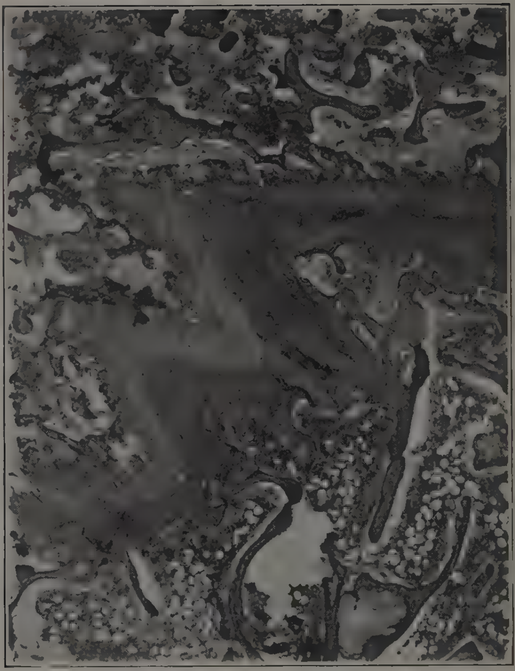

Fig. 13. Section from Proximal Metaphysis of Femur, Pig 9769 (Photomicrograph)

This shows a very irregular epiphyseal cartilage. The columns of cartilage cells in some places are also very irregular. A rather wide layer of osteoid is in close proximity.

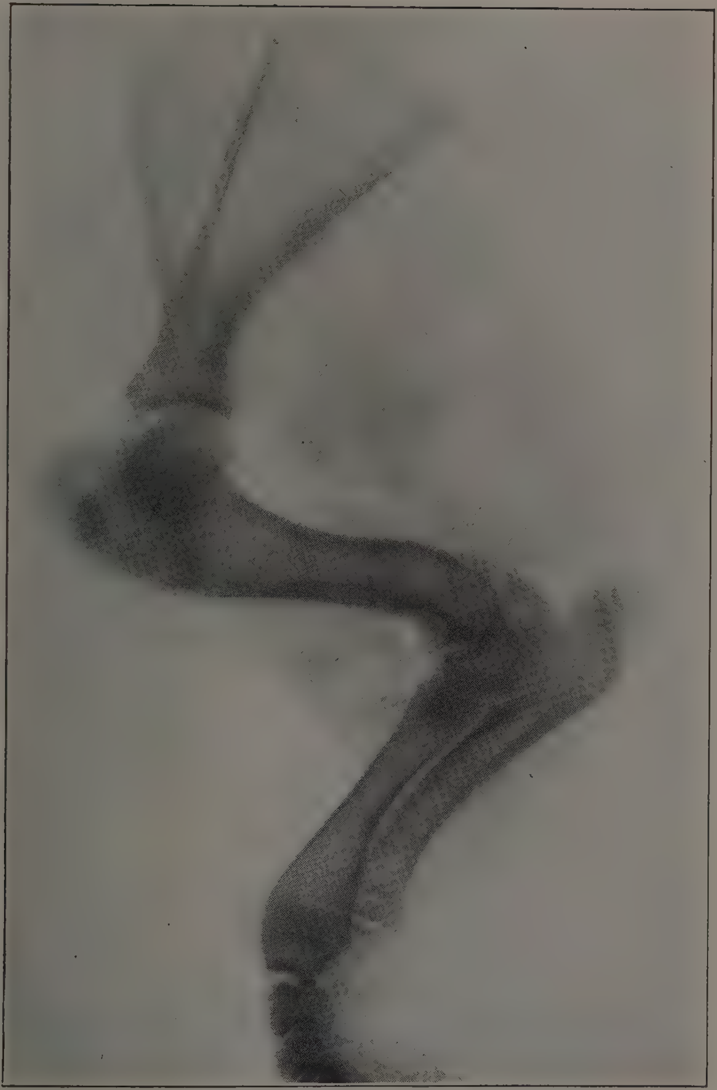

Fig. 14. Left Fore Leg, Pig 9799 (Roentgenograph)

A convex shadow situated about midway of the posterior border of the scapula marks an area of periosteal thickening. The slightly uneven contour of the border of the glenoid cavity indicates a roughened cartilage. There is another area of periosteal thickening on the anterior surface and near the distal extremity of the humerus. The scapula and humerus show evidence of moderate calcium loss, the radius slight loss; the ulna is normal. (The negatives are better adapted for these studies.) See Chart 1.

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University of Minnesota
Agricultural Experiment Station

Plum Investigations II.

The Inheritance of Hardiness

By

M. J. Dorsey, and John Bushnell,
Formerly of Division of Horticulture

UNIVERSITY FARM, ST. PAUL

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Plum Investigations II.

The Inheritance of Hardiness

By

M. J. Dorsey, and John Bushnell,
Formerly of Division of Horticulture

UNIVERSITY FARM, ST. PAUL

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PLUM INVESTIGATIONS II: THE INHERITANCE OF HARDINESS

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INTRODUCTION

In the fruit breeding investigations at the University of Minnesota Fruit Breeding Farm, an attempt has been made to develop hardy varieties of plums with commercial qualities of fruit. Since hardiness is the limiting factor, the general point of attack has been to cross hardy native varieties with tender or semihardy varieties of other species having the desired fruit characters. A large number of variety and interspecies crosses of *Prunus* have been made during the work on this project. The inheritance of hardiness in these has been studied by examining each seedling for the extent of winter injury and then classifying them on the basis of the severity of this injury. The data obtained from a detailed study of available material at the Minnesota Fruit Breeding Farm during the winter of 1917-18 constitute the basis of this report.

The general hardiness problem, particularly in its horticultural aspects, is a subject that has been given considerable attention. It has frequently been pointed out in the horticultural literature that in collections of fruit varieties there are conspicuous differences in the degree and localization of winter injury in different parts of a tree, as well as among the different individuals. However, as pointed out by Dorsey and Bushnell (1920) no cultural methods or protective treatments have been developed which have proved adequate to prevent serious injury when a variety is grown too far north of its normal range. The origination of hardy varieties by breeding appears to be the most effective method at hand of extending fruit-growing northward, as is well illustrated by the improved hardy varieties which are being introduced from the plant breeding stations in Canada and the northern states.

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[1] The data upon which this bulletin is based were secured by the authors while connected wtih the Minnesota Agricultural Experiment Station. Most of the data were secured in the "test winter" of 1917-18 which was unusually severe. Preparation of the manuscript was delayed with a view to gaining supporting data and observations. The mass of material to be handled and the comparisons made consumed more time than was expected. The severance of connections and the removal of both of the authors to other institutions were the final factors in so long delaying the publication.

As yet, the literature on the genetic phases of hardiness is relatively meager. The work of Hansen (1903, 1904, 1906, 1908, and 1911) in South Dakota, Patten in Iowa, and a number of other breeders such as Williams in Nebraska, has demonstrated that hardy varieties can be obtained from interspecies hybrids when the parents differ in hardiness. This principle has also been recognized in the experiments at the Central Experimental Farm in Canada by Saunders (1894, 1896, 1902, and 1911) and Macoun (1898, 1899, 1900, 1906, 1908, and 1909) in the breeding investigations with the apple and other fruits. Hansen's work was among the first attempts with the plum, and he has produced a number of varieties which have proved of value in the northern Great Plains. These have been secured largely from crosses between *Prunus triflora*[1] and *P. americana* or *P. besseyi*. Some investigations with material other than plums will be of interest in this connection. Data published by Chandler (1913) show that gradations in hardiness occur in open pollinated peach seedlings, when classified according to the percentage of buds killed. Nilsson-Ehle (1911 and 1912) found that winter hardiness in wheat segregates in the F_2, and that types can be produced in later generations which are homozygous for varying degrees of winter hardiness.

This investigation, therefore, is primarily a study of the effect of a given set of conditions upon a population in Prunus, representing many different lines of descent and many different genetic combinations. The heterozygous condition of these seedlings is shown by comparing the great variation in injury with that of an equal number of individuals of a single variety which respond similarly. The interest of the plum breeder who is concerned with the development of hardy varieties will center around those lines of descent which have given rise to hardy individuals of greatest commercial promise, as well as in the methods employed in this study.

MATERIALS

Since the varieties of the species used in plum breeding at the Minnesota Fruit Breeding Farm are generally self-sterile, this report is necessarily based upon F_1 progeny. The parents of the hybrids under observation during the winter of 1917-18 were from five species, covering a wide range in hardiness, fruit, and tree characters. As the plums have been carefully described by Hedrick et al. (1911), the parents used need merely be listed here with a brief statement of their hardiness.

The varieties of *P. americana* are generally hardy in Minnesota. In some localities they show slight browning or injury to the terminal buds, but this has not often occurred at the Fruit Breeding Farm, except when cultural conditions induced late growth. The varieties selected as having the greatest promise as parents were Ames, De Soto, Howard Yellow, Jewell, South Dakota 22, 23, and 33, Topa, Wastica, Wolf (freestone), Wyant, and a native unnamed seedling, referred to in the tables as *"P. americana."*

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[1] *P. triflora* is the same as *P. salicina* Lindley.

A single variety of *P. nigra*, Winnipeg, selected from seed collected near Winnipeg, Manitoba, was used. This variety has been one of the hardiest of the plum collection.

The Sand Cherry, *P. besseyi,* was originally collected in South Dakota, along the Missouri River near Pierre, by N. E. Hansen of the South Dakota Agricultural Experiment Station. Seedlings from this source have been semihardy at the Fruit Breeding Farm. The hybrids with the Sand Cherry, as Compass and Opata, have also shown slight injury during average winters.

The varieties of *P. triflora* which were used as parents are tender in Minnesota when unprotected. Burbank, Earliest of All, Red June, Santa Rosa, and Satsuma were used with the hope of getting greater firmness of flesh and greater persistence when ripe. The *P. triflora* hybrids introduced by Burbank, such as America, Climax, First, Formosa, Gold, and Shiro, having largely the characteristics of *P. triflora,* are as tender as the pure varieties. They were selected for parents primarily because of their fruit size and desirable characters of flesh. On the other hand, the *P. americana* × *P. triflora* hybrids, Winona, Bursota, Stella, Wakapa, and Wohonka, which have also been used extensively, have been sufficiently hardy to endure the Minnesota winter conditions at the Fruit Breeding Farm, but with much flower bud killing.

None of the plants of *P. pissardi* has withstood the Minnesota winters when grown in the open.

The crosses were made in 1911 and 1912 by Charles Haralson, on trees growing in tubs in the greenhouses. Greenhouse pollination is more successful in most seasons than outdoor crossing, because unfavorable weather so frequently prevails at the blooming period. At the time of the "test winter" of 1917-18, the trees from the 1911 crosses were six years old from seed and those from the crosses of 1912 a year younger. The plots have been cultivated from the first without a cover crop. The soil is a dark rich loam, and the trees have made good growth each season altho some of the seedlings have matured late. The plots have no appreciable protection by windbreaks or topography.

WINTER OF 1917-18

Individual trees were examined for evidence of winter injury in the spring of 1916, again in 1917, and finally at the close of the winter of 1917-18. The winter of 1917-18 has been called by horticulturists a "test winter" because of the widespread and severe injury to fruit trees. At the Fruit Breeding Farm the injury from this test winter was so much more pronounced and so much more readily measured than in the previous years that the comparative hardiness of the seedlings has been based largely upon their reaction to the conditions of this winter.

The temperature and precipitation record of 1917-18, together with records of the preceding winter, are shown in Figure 1. The graphs were made from records of the Minneapolis Weather Bureau, the nearest point at which weather records are taken. The temperature curves, made from hourly readings, show relatively accurately the daily fluctuations and daily extremes, as well as periods above and below the freezing points.

The record of 1916-17 is included, for in many respects it was very similar to the test winter, yet trees survived 1916-17 to be injured during 1917-18. In comparing the two winters, it may be noted that the minimum temperature was the same both years, reaching —25°F. The periods below freezing were more prolonged and of lower temperature in 1916-17 than in 1917-18. Both years were characterized by a deficiency of precipitation during the fall and early winter. In 1916-17 there was snow protection after the middle of December, but during 1917-18 there was very little snow until the middle of February.

The features which may have been responsible for the excessive injury in 1917-18 are pointed out on the graph. The freeze on October 12, when the thermometer reached 22°F, was not abnormal of itself, but the season of 1917 had begun late the previous spring and the growing season had been shifted so that the trees were not ripened and dormant as they usually are in early October. However, no injury could be detected immediately after this freeze; no direct evidence was collected that an unusual degree of injury had occured. On the other hand, during the alternate periods of thawing and freezing in February and March the discoloration of the wood and the killing of the buds was very evident and was carefully recorded. This injury in the late winter was probably associated with the break in the rest period, and it may be noted that this break occurred as early as February in spite of the fact that the rest period started late the preceding fall.

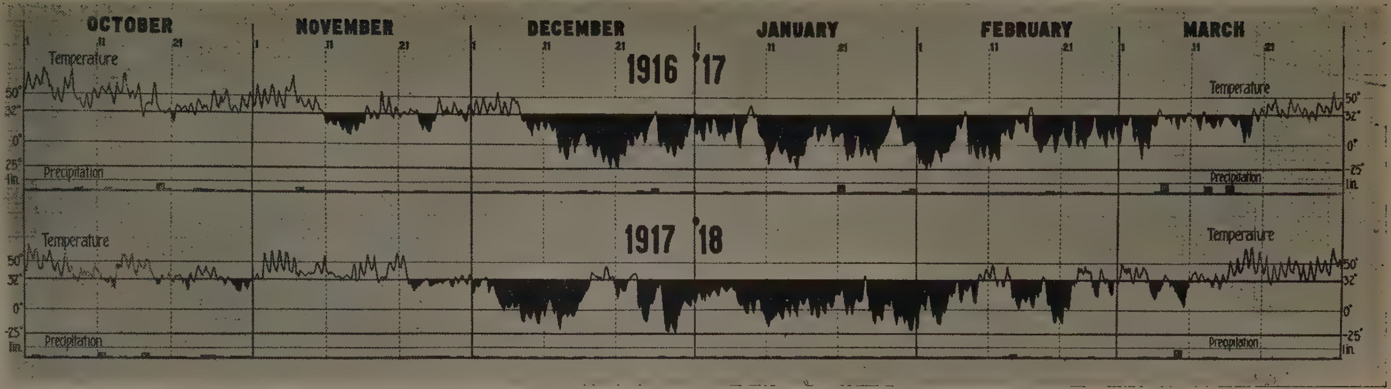


Fig. 1. The Temperature and Precipitation Records of the Winters of 1916-17 and 1917-18.

The winter killing was more severe in 1917-18. Note (1) the freeze on October 12, (2) the alternate periods of thawing and freezing in February and March, and (3) the very light precipitation throughout the winter.

To summarize the significant features of the test winter of 1917-18, four things stand out: (1) the lateness of the previous growing season; (2) the dry soil in the fall and light snowfall during the winter; (3) the freeze in October; and (4) the alternate periods of thawing and freezing in February and March.

TYPES OF WINTER INJURY

Following the winter of 1917-18 the most conspicuous and most readily measured type of injury in the plum hybrids under observation was the killing back of the twigs and branches. It was found, however, in many trees in which this type of injury was not appreciable that the wood and bark were seriously browned or that a large percentage of the buds were dead. In attempting to classify the hybrids no single category seemed adequate; so in tabulating the data the progeny have been classified under three distinct headings: (1) the killing back; (2) the discoloration of the wood; and (3) the percentage of flower buds killed.

WINTER KILLING

During the four years the seedlings were in the field, prior to the first critical examination in 1916, 366 of the 1322 original trees died. The mortality due to accidents of cultivation was light, consequently the greater part were winter killed by the relatively mild winters prior to 1916. The trees eliminated in this way were undoubtedly the most tender individuals of the crosses. During the test winter 49 more were killed, 59 were killed back to the ground but sprouted later from the roots, and 74 were killed to within a foot or two of the ground. The latter are considered as killed back to the line of snow protection.

KILLING BACK OF TWIGS

The average degree of killing of the twigs and branches of the individual trees was readily estimated and together with the more severe killing back of the entire tree, gives a convenient and logical basis for classification of the entire progeny. The killing of the terminal bud has been included under this general type of injury, for it appears to be more closely correlated with injury to the tip of the twig than with the general killing of the flower buds. It is therefore considered to be the slightest degree of killing back of the twigs.

DISCOLORATION OF THE WOOD AND BARK

The records of the intensity of the discoloration in the wood and bark were taken in early spring, before growth started, by making a slanting cut through the bark into the wood to the depth of about three or four annual growths. The cut was made about fifteen inches above the ground on the south side of the trunk rather than on the north side, because in many trees there was deeper browning upon the south side and the greatest injury was purposely taken as the index. The injury records were taken on the trunk instead of upon the main branches or twigs, as the browning was progressively deeper towards the trunk. The degree of browning in the cortex followed that of the wood closely, being seldom darker but often lighter. Consequently, browning in either could be taken as the index of injury but in the tables only the wood browning is reported.

FLOWER BUD KILLING

In determining the percentage of flower buds killed, terminal twigs bearing fruit buds were cut and labeled from all of the trees of each cross, before growth started in the spring, and brought into the laboratory. The fruit buds were then cut transversely near the base and the number of flower buds killed was recorded. The percentages determined in this way were checked in the orchard at bloom by studying the number of flowers arising from the fruit buds, taking three to four as the usual number of flowers borne in each fruit bud. Unfortunately, 116 trees did not bear flower buds so the classification on this basis does not include the entire progeny.

DWARFS

In practically all the crosses 10 per cent or more of the trees were less than three feet tall. Most of these had a peculiar dwarf habit of growth. Many were less than two feet high. As they were protected in a measure by adjacent taller plants, and by the snow during part of the winter, and therefore were not exposed to the same severe conditions as the taller trees, they are not included in the detailed classification of the tables.

METHODS OF CLASSIFICATION

The data included in this report comprise 120 variety crosses, including 1322 individuals. In taking notes in the field each living tree of normal height was examined. First the average killing back was measured on several typical twigs. Then an incision was made in the trunk, and the color of the wood recorded as "clear," "slightly brown," "medium brown," or "dark brown," representing the uninjured wood and three degrees of injury. Later, several twigs were collected from each tree, taken to the laboratory, and the fruit buds carefully examined to determine the percentage of flower buds killed.

In general it was found that injury to one part of the tree was accompanied by injury in other parts; particularly was this the case where the injury was severe. Therefore, in condensing the field notes into the tables, the progeny of each cross have been grouped into frequency distributions under the headings of degree injury. This method facilitates the comparison of the reaction of the entire progeny of a single cross with the entire progeny of any other cross, but it does not show the reaction of the individual trees of each progeny under the three separate categories. That is, in a given progeny there may be a number of the trees with severe browning of the wood and also a number with a percentage of the buds killed; but the condensed tables do not show that the trees with the wood injured were also the ones with the buds killed. However, a critical study of the tables will show (1) that where the progeny are all hardy under one category that they are practically all hardy under the other two categories, and (2) that where a number are injured under one heading approximately the same number are found to be injured under the other headings. To illustrate the variations that occur in the individual differences in the localization of injury, Table I is presented as a typical sample of the field notes.

TABLE I

INDIVIDUAL RECORDS OF TWENTY-SIX CONSECUTIVE TREES OF A BURBANK × DE SOTO CROSS

Tree Number	Dwarfs and trees killed out	Killing back of twigs	Condition of wood	Percentage flower buds killed
1	....	None	Slight brown	No flower buds
2	....	None	Clear	....
3	Killed before 1917	....	....	....
4	....	None	Slight brown	No flower buds
5	Killed before 1917	....	....	....
6	Dwarf	....	....	....
7	....	None	Medium brown	No flower buds
8	Killed before 1917	....	....	No flower buds
9	....	None	Clear	No flower buds
10	....	None	Clear	No flower buds
11	Killed before 1917	....	....	....
12	....	None	Clear	No flower buds
13	Dwarf	....	....	....
14	....	1 inch	Clear	No flower buds
15	Killed before 1917	....	....	....
16	Killed before 1917	....	....	....
17	....	2 inches	Slight brown	10%
18	Dwarf	....	....	....
19	Killed before 1917	....	....	....
20	Killed before 1917	....	....	....
21	....	1 inch	Clear	10%
22	Dwarf	....	....	....
23	Killed before 1917	....	....	....
24	Killed before 1917	....	....	....
25	Killed before 1917	....	....	....
26	....	None	Clear	No flower buds

In this table it may be noted that eleven trees were killed before 1917, four were dwarfs, five (Trees 2, 9, 10, 12, and 26) were completely hardy, and six were slightly injured in one or more of the three regions examined. Of the last six (Trees 1, 4, 7, 14, 17, and 21), three showed slight twig killing, four wood injury, and the two with flower buds had about 10 per cent killed. Thus the total number showing slight injury is frequently somewhat greater than the number slightly injured under any single heading of the condensed tables.

Before taking up the tabulations it should be re-emphasized that in these classifications the attempt has been made to detect very slight injury, and that the trees showing only slight injury would from casual examination be classed as entirely hardy; during an ordinary winter they would be completely hardy. In the discussion of the tables, therefore, the individuals which were killed back only in the tip, which show slight or even medium browning of the wood, and in which 25 per cent or less of the buds were killed, are called "hardy," and can be recommended for commercial planting under conditions similar to those at the Fruit Breeding Farm in Minnesota.

Turning to a consideration of the series of tables, it is evident from the headings that tender progeny are included under "Number killed before 1917" and "Trees severely injured 1917-18." The balance of the trees taller than three feet included in the column headed "Trees examined in more detail," are then further classified under the three main headings of "Killing back of twigs," "Discoloration of wood" and "Percentage of buds killed." In the last category it will be seen that a single column includes those that failed to produce flower buds.

THE SEEDLINGS CLASSIFIED ACCORDING TO WINTER INJURY

In presenting the tabulated data the various crosses are grouped according to the parental species. Thus the numerous crosses which include only *P. americana* and *P. triflora* in various combinations are given in the first series of Tables II, III, IV, and V. This series is followed by the crosses in which *P. nigra* enters. Then the hybrids with *P. besseyi,* and lastly those with *P. pissardi.*

As may be noted by a critical examination of the tables, the different varieties used as parents within any species produce very similar progeny when classified on the basis of hardiness. For that reason the discussion is confined to the behavior of the species groups. The plum breeder particularly interested in the relative merits of the different varieties as parents will find that the same scheme of classification is used throughout the series of tables and that the progeny of any particular variety can be readily compared with that of any other. In listing the crosses the usual method of giving the pistillate parent first has been followed.

TABLE II

A CLASSIFICATION OF F_1 HYBRIDS ACCORDING TO THE DEGREE OF WINTER INJURY. CROSSES OF *P. americana* WITH (1) *P. americana*, (2) *P. americana* × *P. triflora*, (3) *P. triflora*

	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Trees severely injured 1917-18			Trees examined in more detail	Classification of trees which survived the winter of 1917-18																		
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
				Killed top and root	Killed to ground	Killed to snow		Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. americana × *P. americana*																										
Zekanta × *P. americana*	20	1	..	..	..	..	19	..	..	..	..	13	6	..	1	..	18	2	..	..	..	..	..	..	..	17
P. americana × (*P. americana* × *P. triflora*)																										
Bursota × DeSoto	11	8	1	..	..	..	2	..	..	..	..	2	..	..	..	1	1	..	..	..	..	..	..	..	..	2
Winona × *P. americana*	21	8	4	..	..	1	8	..	..	2	1	1	4	..	..	..	8	1	..	..	..	..	..	..	3	4
Winona × *P. americana*	23	1	1	..	..	..	21	..	..	..	2	11	8	..	1	3	17	1	..	..	..	..	..	..	..	20
Winona × Wyant	9	4	..	..	..	..	5	..	..	1	..	1	3	..	2	2	1	2	..	..	..	..	1	..	1	1
Stella × *P. americana*	5	4	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Stella × Wyant	5	2	1	1	..	..	1	..	..	1	..	..	..	1	..	..	..	..	1	..	..	..	..	..	..	..
Wakapa × DeSoto	5	2	1	..	..	..	2	..	..	..	..	1	1	1	..	1	..	..	..	..	..	..	..	2	..	..
Wakapa × *P. americana*	5	2	2	..	..	..	1	..	..	..	..	1	..	..	..	1	..	..	1	..	..	..	..	..	..	..
Wakapa × Wyant	22	11	..	1	..	1	9	..	..	1	..	8	..	4	..	2	3	4	..	..	..	..	..	..	..	..
Total	106	42	10	3	..	2	49	..	..	5	3	25	16	6	3	10	30	8	2	..	..	..	1	2	4	32
P. americana × *P. triflora*																										
Burbank × DeSoto	44	21	5	..	..	..	18	..	..	..	2	4	12	..	2	3	13	6	..	..	..	1	1	2	2	6
Burbank × Howard Yellow	8	5	1	..	..	..	2	..	..	..	..	1	1	..	..	..	2	..	..	..	..	..	..	..	..	2
Burbank × Jewell	5	1	..	..	..	..	4	..	..	..	..	1	3	..	1	3	..	..	..	..	..	..	..	1	1	2
Burbank × *P. americana* ..	11	7	1	..	..	..	3	..	..	..	..	..	3	1	..	..	2	1	..	..	..	..	..	..	..	2
Burbank × Topa	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
DeSoto × Burbank	26	2	3	..	..	..	21	..	..	..	2	11	8	..	..	..	21	1	..	..	..	..	..	..	..	20
Earliest of All × DeSoto	7	2	..	..	..	..	5	1	..	..	..	2	2	2	..	..	3	..	..	..	..	..	1	1	3	..
Earliest of All × Jewell	3	1	..	..	..	..	2	..	..	..	2	..	..	..	1	..	1	..	..	..	..	..	..	..	2	..
Howard Yellow × Satsuma	6	4	..	..	..	..	2	..	..	..	..	1	1	..	..	..	2	..	..	..	..	..	..	..	..	2
Jewell × Burbank	4	1	..	..	..	..	3	..	..	..	..	3	..	..	..	..	3	..	..	..	..	..	..	..	..	3
Santa Rosa × Jewell	3	..	..	..	..	..	3	..	..	..	1	1	1	1	2	..	..	..	..	..	..	..	..	..	1	2
Santa Rosa × South Dakota 33	1	..	..	..	..	..	1	..	..	..	..	1	..	..	1	..	..	1	..	..	..	..	..	..	..	..
Santa Rosa × Topa	1	..	..	..	..	..	1	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	..	1
South Dakota 23 × Satsuma	1	..	..	..	..	..	1	..	..	..	..	..	1	..	..	1	..	..	..	..	..	..	..	..	..	1
South Dakota 33 × Burbank	1	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	1
Topa × Santa Rosa ...	5	..	..	..	..	..	5	..	..	..	..	2	3	..	..	..	5	..	..	..	..	..	..	..	..	5
Wyant × Burbank	13	..	..	..	..	..	13	..	..	..	..	5	8	..	..	1	12	..	..	..	..	..	..	..	..	13
Wyant × Santa Rosa ...	12	1	3	..	..	..	8	..	..	..	..	7	1	..	..	..	8	..	..	..	..	..	..	..	..	8
Wyant × Satsuma	4	..	..	..	..	..	4	..	..	..	..	2	2	..	1	1	2	..	..	..	..	..	..	..	..	4

P. AMERICANA × P. AMERICANA

The first cross listed in Table II is between Zekanta, a hardy variety of *P. americana,* and a hardy seedling of the same species. Tip killing occurred in a majority of the trees of this cross. Altho this type of injury occurs but rarely to this species in Minnesota, it was found to have taken place in some of the varieties under cultivation following the winter of 1917-18. The progeny of this combination were practically all as hardy as the parents, meeting the expectation as to hardiness when parents of the native species are used, but none of the individuals was sufficiently outstanding in fruit characters to justify further testing.

P. AMERICANA × (P. AMERICANA × P. TRIFLORA)

More accurately this heading should be reversed, for the hardy hybrids of *P. americana* × *P. triflora* were used as the pistillate parent in every cross. In combinations of the second group in Table II between hardy varieties, *P. americana,* and the somewhat less hardy varieties in which both *P. americana* and *P. triflora* enter, the progeny fall into two extreme categories, with but very few intermediates; first, the seedlings which were killed, and second, those which were hardy. The totals show that at least 40 of the progeny were as hardy as the parents and that 47 were killed. With one of the parents from the hardy species *P. americana,* it will be noted that the introduction of *P. triflora* has greatly reduced the proportion of hardy seedlings in the progeny. The significance of this genetically will be taken up later.

P. AMERICANA × P. TRIFLORA

The general distribution of the progeny in this third group of Table II is very similar to that of the preceding group. The proportion of hardy individuals is even greater, altho *P. triflora* is much more tender than the varieties *P. americana* × *P. triflora* which were used as parents in the preceding group. It appears from the totals in this combination of hardy by tender parents, that even more hardy than tender progeny have appeared. This is significant in view of the fact that up to the time of planting in the test plots the seedlings had not been subjected to temperatures which would kill off the tender individuals when young. The failure of many seeds to germinate, however, might account for this apparent inconsistency.

Dealing more specifically with the individual crosses of this combination it may be noted that toward the bottom of Table II there is a group in which none of the seedlings are killed. The tables were compiled without reference to which species was used as the female parent, the reciprocal crosses being arranged in the table according to the alphabetical sequence of the pistillate parents. Fortunately the number of trees under observation is large enough to permit a significant comparison of the reciprocals. These have been brought together in Table III.

By referring to Table III it will be seen that the distribution of the reciprocals is strikingly different. When *P. americana* is used as the pistillate parent almost all the progeny are hardy. Where *P. triflora* is used as the pistillate parent approximately one half of the progeny are tender. Altho these data are not entirely consistent, this difference in the reciprocal crosses can hardly be attributed to experimental error and hence is suggestive in that it indicates the hardier parent should be used as the pistillate parent in order to secure hardy seedlings. This point is of sufficient importance to justify further study.

P. AMERICANA × P. TRIFLORA HYBRIDS

This group is the fourth of the series of *P. americana* crosses. In the production of hardy progeny the *P. triflora* hybrids are about on a par with the pure *P. triflora* varieties; and while the progeny reported in Table IV show a greater tendency to segregate than those of the preceding group, in general these seedlings also fall largely into two groups characterized by hardiness on one hand and a lack of it on the other. As before, all of the individuals of the hardy group are not as hardy as the *P. americana* parent but a large proportion of the progeny approach the hardy parent in hardiness. Again the data can be divided according to which species served as the pistillate parent. Practically all the *P. americana* × *P. triflora* progeny are hardy; and the reciprocals approximate a 1:1 ratio.

From a fruit-breeding standpoint it is noteworthy that the species combinations *P. americana* with *P. triflora* and the *P. triflora* hybrids have not only produced a remarkably large proportion of hardy progeny, but among these hardy progeny have been found individuals with very desirable fruit. The results from using these species in Minnesota correspond with those of other plum breeders, particularly C. G. Patten in Iowa and Theodore Williams in Nebraska, in that sufficient hardiness for commercial purposes has been obtained in seedlings with very desirable fruit. In fact, some of the seedlings of this combination are so outstanding in tree and fruit as to give promise of replacing the best varieties of either of the parent species.

TABLE III

Classification of Progeny from Reciprocal Crosses of (1) *P. americana* × *P. triflora* and (2) *P. americana* × *P. triflora* Hybrids

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																		
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. americana × *P. triflora*	72	8	6	..	..	..	58	..	..	..	2	31	25	..	1	3	54	1	..	..	..	..	..	..	..	57
P. triflora × *P. americana*	85	38	8	..	..	..	39	..	..	..	5	11	22	4	7	7	21	8	..	..	..	1	2	4	9	15
P. americana × *P. triflora* hybrids ..	43	..	2	..	..	..	41	..	..	..	5	21	15	1	2	1	37	6	..	..	..	..	..	..	..	35
P. triflora hybrids × *P. americana*	196	55	36	2	3	5	95	..	3	8	14	58	11	13	34	21	27	35	1	2	..	5	..	1	7	44

TABLE IV

Crosses of *P. americana* with *P. triflora* Hybrids

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																		
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. americana × *P. triflora hybrids*																										
America × *P. americana* ..	2	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
America × Jewell	1	..	..	..	..	..	1	..	..	..	..	1	..	..	..	..	1	1	..	..	..	..	..	..	..	..
America × Wyant	6	2	3	..	..	..	1	..	..	..	..	1	..	..	1	..	..	1	..	..	..	..	..	..	..	..
Ames × Formosa	3	..	1	..	..	..	2	..	..	..	..	2	..	..	..	..	2	1	..	..	..	..	..	..	..	1
Climax × Wyant	10	2	3	1	..	..	4	1	..	..	..	1	2	1	..	3	..	..	..	..	..	1	..	1	2	..
DeSoto × America	4	..	1	..	..	..	3	..	..	..	1	1	1	..	..	..	3	1	..	..	..	..	..	..	..	2
DeSoto × Formosa	2	..	..	..	..	..	2	..	..	..	..	1	1	..	..	..	2	1	..	..	..	..	..	..	..	1
DeSoto × Shiro	5	..	..	..	..	..	5	..	..	..	2	1	2	..	..	..	5	..	..	..	..	..	..	..	..	5
First × *P. americana* ..	14	9	..	..	..	1	4	..	..	1	..	3	..	..	2	1	1	2	..	..	..	1	..	..	1	..
First × Wyant	2	..	..	..	..	1	1	..	1	..	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	..
Gold × Howard Yellow	10	5	4	..	..	..	1	..	..	..	..	1	..	..	..	..	1	..	..	..	..	..	..	..	..	1
Gold × *P. americana* ..	13	7	1	1	..	..	4	..	..	2	1	1	..	2	1	..	1	2	..	1	..	..	..	..	1	..
Gold × South Dakota 33	7	4	1	..	..	..	2	..	1	..	..	..	1	1	..	..	1	..	1	..	..	1	..	..	..	..
Gold × Topa	4	1	1	..	..	..	2	..	..	..	..	1	1	1	1	..	..	1	..	1	..	..	..	..	..	..
Gold × Wyant	4	3	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	1
Jewell × Formosa	1	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	1	..	..	..	..	..	..	..	..
Shiro × Ames	16	6	3	..	2	..	5	..	..	1	..	3	1	..	1	2	2	2	..	..	..	..	..	..	..	3
Shiro × De Soto	11	1	4	..	..	..	6	..	..	..	2	3	1	..	2	3	1	2	..	..	..	..	..	..	..	4
Shiro × Howard Yellow	18	2	2	..	..	..	14	..	..	2	5	7	..	5	5	2	2	9	..	..	..	..	..	..	..	5
Shiro × Jewell	9	2	2	..	..	1	4	..	..	..	1	3	..	..	1	..	3	1	..	..	..	..	..	..	..	3
Shiro × *P. americana* ..	21	3	3	..	..	2	13	..	1	1	2	8	1	2	7	3	1	4	..	..	..	..	..	..	..	9
Shiro × South Dakota 33	31	6	4	..	1	..	20	..	..	1	1	16	2	1	9	2	8	7	..	..	..	..	..	..	..	13
Shiro × Topa	2	..	..	..	..	..	2	..	..	..	1	1	..	..	1	..	1	..	..	..	..	..	..	..	..	2
Shiro × Wolf	9	1	2	..	..	..	6	..	..	..	..	5	1	..	..	3	3	2	..	..	..	1	..	..	..	3
Shiro × Wyant	6	1	1	..	..	..	4	..	..	..	1	3	..	..	3	1	..	1	..	..	..	..	..	..	3	..
South Dakota 22 × Formosa	1	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	1
South Dakota 22 × Shiro	14	..	..	..	..	..	14	..	..	..	..	11	3	..	1	..	13	2	..	..	..	..	..	..	..	12
Wastica × First	6	..	..	..	..	..	6	..	..	..	1	4	1	..	..	..	6	..	..	..	..	..	..	..	..	6
Wyant × Gold	7	..	..	..	..	..	7	..	..	..	1	1	5	1	1	1	4	..	..	..	..	..	..	..	..	7
Total	239	55	38	2	3	5	136	1	3	8	19	79	26	14	36	22	64	41	1	2	..	5	..	1	7	79

TABLE V

Crosses of Hardy Hybrids of *P. americana* × *P. triflora* with (1) *P. americana* × *P. triflora*, (2) *P. triflora*, (3) *P. triflora* Hybrids

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																	
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
(*P. americana* × *P. triflora*) × (*P. americana* × *P. triflora*)																										
Winona × Bursota	4	1	1	..	..	1	1	..	..	..	..	1	..	..	1	..	..	..	..	..	..	..	..	..	..	1
Stella × Bursota	15	1	1	..	..	..	13	..	..	..	..	8	5	..	..	..	13	2	..	..	..	..	..	..	1	10
Wakapa × Bursota	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Wakapa × Winona	3	2	..	..	..	..	1	..	..	..	..	..	1	..	1	..	..	..	..	..	..	1	..	..	..	..
Total	24	5	3	..	..	1	15	..	..	..	..	9	6	..	2	..	13	2	..	..	..	1	..	..	1	11
(*P. americana* × *P. triflora*) × *P. triflora*																										
Burbank × Bursota	8	2	1	..	..	..	5	..	..	..	..	1	4	1	..	..	4	2	..	1	..	..	..	..	..	2
Winona × Burbank	15	4	..	..	..	..	11	..	1	1	2	6	1	6	4	1	..	3	4	1	1	1	..	..	..	1
Winona × Santa Rosa ..	22	5	1	..	..	..	16	1	..	2	2	7	4	9	3	1	3	7	4	3	1	..	..	1	..	..
Santa Rosa × Bursota	2	..	..	..	1	..	1	..	..	..	..	1	..	..	..	..	1	..	..	..	..	..	..	..	..	1
Stella × Burbank	3	1	..	..	..	..	2	..	..	..	..	1	1	..	..	..	2	1	..	..	..	..	..	..	..	1
Wakapa × Burbank	3	2	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Wakapa × Earliest of All	2	..	..	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Wohonka × Earliest of All	2	..	..	..	..	..	2	..	..	..	2	..	..	..	2	..	..	..	1	..	..	..	1	..	..	..
Total	57	14	2	3	1	..	37	1	1	3	6	16	10	16	9	2	10	13	9	5	2	1	1	1	..	5
(*P. americana* × *P. triflora*) × *P. triflora* hybrids																										
Shiro × Bursota	10	3	1	..	..	..	6	..	..	..	2	3	1	2	1	3	..	2	..	..	..	..	..	1	..	3
Stella × Climax	5	..	1	1	..	1	2	1	..	..	1	..	..	2	..	..	..	..	..	..	..	1	..	1	..	..
Wakapa × Climax	14	7	..	..	2	2	3	..	..	1	..	2	..	2	1	..	..	..	..	..	1	2	..	..	..	..
Wakapa × First	45	13	6	..	1	8	17	2	2	1	2	10	..	9	7	1	..	5	7	4	1	..	..	..	..	..
Wohonka × Formosa	3	1	..	..	..	..	2	..	..	..	..	1	1	2	..	..	..	..	1	..	..	..	..	..	..	1
Total	77	24	8	1	3	11	30	3	2	2	5	16	2	17	9	4	..	7	8	4	2	3	..	2	..	4

CROSSES WITH THE HARDY HYBRIDS OF P. AMERICANA × P. TRIFLORA

The hybrid varieties of *P. americana* × *P. triflora* have been used in a number of species combinations forming an interesting series similar to the preceding *P. americana* crosses. The first of this series might be considered to be the cross of *(P. americana × P. triflora)* × *P. americana* reported in Table II. It will be recalled that about half of the progeny were killed and that the remainder were nearly as hardy as the parents.

(P. AMERICANA × P. TRIFLORA) × (P. AMERICANA × P. TRIFLORA)

This group forms the second in the series. Altho the number of individuals in the progeny of these crosses is small (Table V) more than half of the normal trees are in the hardy classes, and a few individuals are classified as being hardier than either parent. This is characteristic of this series.

(P. AMERICANA × P. TRIFLORA) × P. TRIFLORA AND P. TRIFLORA HYBRIDS

The individuals of the second and third groups (Table V) into which the tender *P. triflora* has entered so extensively again form definite groups at the hardy and tender extremes.

The F_1 individuals of this series vary much in tree and fruit characters as well as in hardiness. It will be noticed that dwarf trees appear in relatively small numbers and that about one fourth of the trees of each progeny were killed before 1917. In addition to the production of individuals hardier than either parent it will be seen that in the progeny with the larger numbers the distribution as to hardiness ranges more toward the greater degrees of injury than in the *P. americana* × *P. triflora* crosses.

CROSSES WITH P. NIGRA

P. nigra is a hardy northern species. Its native habitat extends northward and eastward from western Minnesota across Canada and into the northern part of the United States in a few areas. It is not so well known among horticulturists because fewer of its varieties have been named. For this reason it has been used in breeding to only a limited extent. It should be stated in this connection that the variety of *P. nigra* used in these crosses came from seed collected near Winnipeg—hence the name.

TABLE VI

Crosses of *Prunus nigra* with (1) *P. americana* × *triflora*, (2) *P. triflora* Hybrids, (3) *P. triflora*, (4) Comparison of Progeny from Crosses of Shiro with *P. americana* and *P. nigra*

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																	
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. nigra × (*P. americana* × *P. triflora*)																										
Winona × Winnipeg	20	11	3	..	..	..	6	..	..	..	..	..	6	..	..	..	6	..	..	..	..	..	..	..	..	6
Stella × Winnipeg	2	1	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	1	..
Wakapa × Winnipeg	5	2	2	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	1
Total	27	14	5	..	..	..	8	..	..	..	..	..	8	..	..	..	8	..	..	..	..	..	..	..	1	7
P. nigra × *P. triflora* hybrids																										
Shiro × Winnipeg	39	3	3	1	..	..	32	..	..	..	1	17	14	7	2	13	10	3	..	..	..	..	..	..	..	29
Gold × Winnipeg	1	..	..	..	..	..	1	..	..	..	..	1	..	..	..	..	1	1	..	..	..	..	..	..	..	..
Winnipeg × Shiro	1	..	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	..	..	1
Total	41	3	3	1	..	..	34	..	..	..	1	18	15	7	2	13	12	4	..	..	..	..	..	..	..	30
P. nigra × *P. triflora*																										
Burbank × Winnipeg	2	1	..	..	..	..	1	..	..	..	..	..	1	..	..	..	1	..	..	..	..	..	..	1	..	..
Santa Rosa × Winnipeg	4	..	..	..	..	..	4	..	..	1	..	2	1	..	1	1	2	3	..	..	..	..	..	..	..	1
Total	6	1	..	..	..	..	5	..	..	1	..	2	2	..	1	1	3	3	..	..	..	..	..	1	..	1
Shiro × *P. americana*	123	22	21	..	3	3	74	..	1	5	13	49	6	8	29	16	21	28	..	..	..	1	..	..	3	42
Shiro × *P. nigra*	39	3	3	1	..	..	32	..	..	..	1	17	14	7	2	13	10	3	..	..	..	..	..	..	..	29

In the crosses recorded in Table VI an opportunity is presented to compare *P. nigra* with *P. americana* as a hardy parent. It will be seen that as large a proportion of the progeny are hardy as in similar crosses where *P. americana* was used. A study of the hardiest of these seedlings in the orchard after the severest winters, indicates that they are even hardier than the hardiest of the *P. americana* progeny.

The only comparable crosses having numbers large enough to illustrate this are those of the two species with Shiro, a tender *P. triflora* hybrid. The comparison is included as the last group in Table VI where it may be noted that the general distribution is very similar to *P. americana,* but that a considerably larger proportion of the *P. nigra* progeny are hardy. Both species cross readily with Shiro but in tree characters the *P. nigra* seedlings are superior. If the F_1 seedlings available for this investigation are to be taken as an index, it may be safely stated that *P. nigra* can be used as a parent in crosses with *P. triflora* with at least as much success as *P. americana.*

CROSSES WITH P. BESSEYI

The distribution of the hybrids reported in Table VII is in marked contrast with that from comparable crosses of *P. americana* and *P. nigra.* About the same proportion were killed prior to 1918, but the remainder, instead of being largely hardy, were more or less severely injured. The injury shows particularly in the killing back of the twigs and in the discoloration of the wood. Less than 20 per cent can be considered commercially hardy in Minnesota.

CROSSES WITH P. BESSEYI HYBRIDS

The first two groups in Table VIII are crosses of *P. besseyi* hybrids with the hardy *P. americana* and *P. nigra* varieties. In both groups there occur individuals that were killed prior to 1917-18 and in the first group a few of the surviving trees that were seriously injured. *P. besseyi* hybrids used as parents are nearly hardy, but when crossed with the hardiest species segregation of tender progeny has occurred.

The remainder of Table VIII includes the crosses of *P. besseyi* hybrids with the *P. triflora* groups. The progeny show a wide range in hardiness with only a small proportion as hardy as the parent. Many of these plots appeared to be almost entirely worthless from the plant breeding viewpoint when examined in the spring of 1918. The *P. besseyi* parents came from South Dakota, and have not been completely hardy in Minnesota. It is probable that selections from farther north would prove more successful in plum breeding.

TABLE VII

CROSSES OF *P. besseyi* WITH (1) *P. triflora*, (2) *P. triflora* HYBRIDS

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																	
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed						
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. besseyi × *P. triflora*																										
Sand Cherry × Satsuma	11	3	..	..	..	4	4	..	..	..	..	..	1	4	..	..	..	..	..	..	..	..	1	2	..	1
P. besseyi × *P. triflora* hybrids																										
Sand Cherry × Climax	60	22	9	1	3	8	17	1	4	1	2	3	4	7	10	..	..	..	..	..	..	3	1	12	1	..
Sand Cherry × Formosa	21	5	3	..	..	2	11	..	1	..	1	1	7	6	2	3	..	..	..	..	2	3	2	..	3	1
Sand Cherry × Gold	6	2	1	..	1	..	2	1	1	..	..	..	..	2	..	..	..	..	..	..	..	1	1	..	..	..
Total	87	29	13	1	4	10	30	2	6	1	3	4	11	15	12	3	..	..	..	..	2	7	4	12	4	1

TABLE VIII

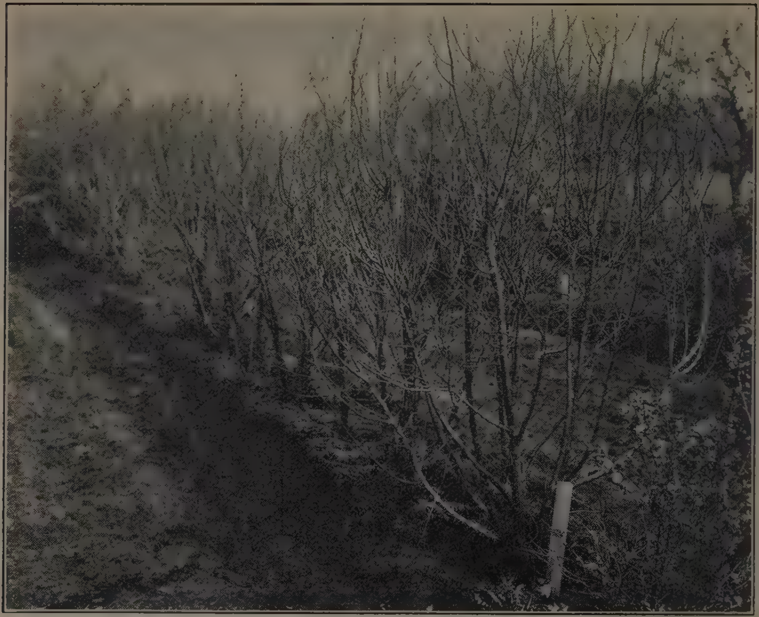
CROSSES OF *P. besseyi* HYBRIDS WITH (1) *P. americana*, (2) *P. nigra*, (3) *P. americana* × *P. triflora*, (4) *P. triflora*, (5) *P. triflora* HYBRIDS

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																		
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. besseyi hybrids × *P. americana*																										
Compass × Howard Yellow	5	..	2	..	..	1	2	..	..	..	..	1	1	..	..	1	1	..	..	..	..	..	..	..	2	..
Compass × *P. americana* ..	12	..	..	..	..	..	12	..	..	1	2	3	6	3	1	5	3	2	..	..	..	..	..	..	..	10
Opata × Wyant	3	2	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Wyant × Opata	5	2	..	..	..	..	3	..	..	..	..	2	1	..	..	3	..	..	..	..	..	..	..	..	..	3
Total	25	4	3	..	..	1	17	..	..	1	2	6	8	3	1	9	4	2	..	..	..	..	..	..	2	13
P. besseyi hybrids × *P. nigra*																										
Compass × Winnipeg	4	..	1	..	..	..	3	..	..	..	..	1	2	..	..	..	3	..	..	..	..	..	..	..	1	2
Opata × Winnipeg	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Total	6	2	1	..	..	..	3	..	..	..	..	1	2	..	..	..	3	..	..	..	..	..	..	..	1	2
P. besseyi hybrids × (*P. americana* × *P. triflora*)																										
Compass × Tonka	12	4	5	..	..	..	3	..	..	..	..	2	1	1	..	1	1	..	..	..	..	..	1	1	1	..
Compass × Winona	10	..	..	..	2	3	5	..	1	..	..	3	1	1	3	1	..	..	..	..	..	1	..	3	1	..
Etopa × Bursota	3	1	1	..	..	..	1	..	1	..	..	..	..	..	..	..	1	..	1	..	..	..	..	..	..	..
Opata × Bursota	6	1	1	2	..	1	1	..	..	..	..	1	..	1	..	..	..	1	..	..	..	..	..	..	..	..
Total	31	6	7	2	2	4	10	..	2	..	..	6	2	3	3	2	2	1	1	..	..	1	1	4	2	..
P. besseyi hybrids × *P. triflora*																										
Compass × Burbank	47	16	3	3	2	3	20	2	1	1	3	12	1	8	10	1	1	3	1	..	..	..	5	9	2	..
Compass × Red June	7	..	1	..	..	..	6	..	..	..	..	2	4	3	2	1	..	..	..	..	1	1	1	..	1	2
Compass × Santa Rosa ...	1	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Compass × Satsuma	28	2	3	1	5	3	14	2	..	2	4	6	..	11	1	2	..	3	..	..	..	1	1	5	4	..
Opata × Burbank	2	1	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Opata × Red June	4	2	..	..	..	..	2	..	..	..	..	1	1	..	2	..	..	..	..	..	..	..	..	..	2	..
Opata × Santa Rosa ...	5	1	1	..	2	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Satsuma × Compass	34	3	6	..	4	8	13	5	..	..	4	4	..	12	1	..	..	2	..	..	..	3	4	4	..	..
Total	128	25	14	4	14	16	55	9	1	3	11	25	6	34	16	4	1	8	1	..	1	5	11	18	9	2
P. besseyi hybrids × *P. triflora* hybrids																										
Compass × Climax	100	44	20	8	7	4	17	..	4	1	4	7	1	11	5	1	..	..	..	1	1	3	9	3	..	..
Compass × Formosa	36	15	2	1	3	..	15	3	1	..	2	7	2	11	1	3	..	4	1	..	..	1	4	1	4	..
Compass × Gold	1	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Compass × Shiro	3	..	2	..	..	..	1	1	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	1	..	..
Opata × Formosa	3	1	..	..	1	..	1	..	..	..	1	..	..	..	..	1	..	..	1	..	..	..	..	..	..	..
Shiro × Compass	3	1	..	..	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

TABLE IX

Crosses of *P. pissardi* with (1) *P. americana*, (2) *P. americana* × *P. triflora*, (3) *P. besseyi*, (4) *P. besseyi* Hybrids

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																	
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. pissardi × *P. americana*																										
P. pissardi × Howard Yellow	1	..	..	..	..	..	1	..	..	1	..	..	..	..	..	..	1	1	..	..	..	..	..	..	..	..
Wyant × *P. pissardi*	1	..	1	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Total	2	..	1	..	..	..	1	..	..	1	..	..	..	..	..	..	1	1	..	..	..	..	..	..	..	..
P. pissardi × (*P. americana* × *P. triflora*)																										
Winona × *P. pissardi*	31	6	9	..	..	2	14	1	1	2	5	5	..	11	3	..	..	8	3	..	..	..	..	..	..	3
Stella × *P. pissardi*	1	..	..	..	..	..	1	..	1	..	..	..	..	..	1	..	..	1	..	..	..	..	..	..	..	..
Wakapa × *P. pissardi*	70	17	7	20	13	8	5	..	1	..	1	3	..	3	2	..	..	1	..	1	2	1	..	..	..	..
Wohonka × *P. pissardi*	13	1	1	2	7	1	1	..	1	..	..	..	..	1	..	..	..	..	..	1	..	..	..	..	..	..
Total	115	24	17	22	20	11	21	1	4	2	6	8	..	15	6	..	..	10	3	2	2	1	..	..	..	3
P. pissardi × *P. besseyi*	5	3	1	..	..	..	1	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	1
P. pissardi × *P. besseyi* hybrids																										
Compass × *P. pissardi*	5	2	..	1	..	..	2	..	1	1	..	..	..	1	1	..	..	1	..	..	..	1	..	..	..	..
Etopa × *P. pissardi*	7	2	2	..	..	3	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Total	12	4	2	1	..	3	2	..	1	1	..	..	..	1	1	..	..	1	..	..	..	1	..	..	..	..



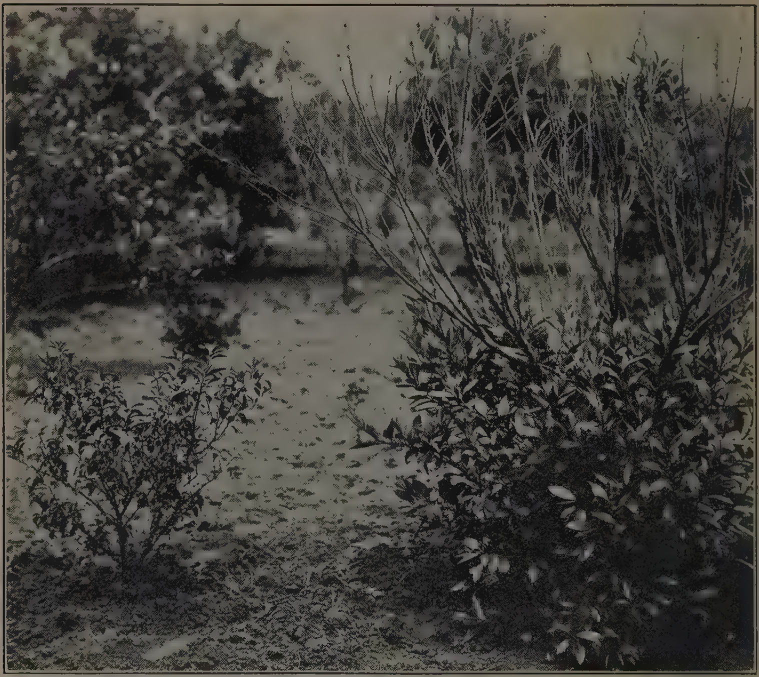


Fig. 2. Upper: Wohonka × *P. pissardi,* a Tender Cross; Lower: *P. besseyi* × Climax, a Dwarf, and One Seedling Killed to the Snow Line

CROSSES WITH P. PISSARDI

P. pissardi is a tender ornamental with practically worthless fruit. The data presented in Table IX are chiefly of interest because of the contrast with the previous data in which *P. triflora* was the tender parent. Practically all of the trees reported in Table IX showed some injury in the tissues examined; only seven could possibly be considered as hardy enough to endure an average Minnesota winter. From the inheritance standpoint these progeny may be classified as intermediate between the two parents in hardiness.

SUMMARY OF THE SPECIES CROSSES

In Table X the totals from the preceding groups are brought together to show the comparative distribution of the F_1 progeny of the various species combinations. The relative hardiness of the progeny of the different combinations is readily seen when summarized in this form. The large proportion of hardy offspring when *P. americana* and *P. nigra* are used as one of the parents is re-emphasized. Likewise, in the combinations in which *P. besseyi, P. pissardi,* and *P. triflora* enter, the number of tenderer seedlings increases.

The bud killing in the different summaries in general follows the wood injury and the killing back. A considerable number of seedlings (116), however, failed to develop fruit buds. In combinations like these if the tender line is drawn to include all which were killed back over two feet or more or killed outright, the number reaches 577 individuals—nearly half of the total. If the commercially hardy forms for Minnesota are limited to seedlings classified in the last two columns of each of the main headings, an approximate idea is reached as to the number from which to select desirable fruiting types. Rated on this basis 475 were sufficiently hardy in the twigs, 329 in the wood, and 325 in the buds. In these blocks of seedlings the individuals which were selected on the basis of superior fruit numbered about fifty. These selections were practically all limited to the commercially hardy group and this number may be considered high in view of the merits of most of them.

This summary presents the limitations encountered in practical breeding with the parents selected. While there is every justification in using some of the combinations listed here in order to secure types for further breeding, it should be clear that the source of hardiness for Minnesota lies in *P. americana* and *P. nigra,* and possibly hardier forms of *P. besseyi,* from farther north in the range of this species. Considerable should be gained, therefore, from this preliminary survey of the relative value of the different species as to sources of hardiness in the F_1.

TABLE X

Summary of Tables II, IV, V, VI, VII, VIII, IX. A Classification of F_1 Hybrids of Species Crosses According to Degree of Winter Injury

				Trees severely injured 1917-18				Classification of trees which survived the winter of 1917-18																		
								Killing back of twigs						Discoloration of wood					Percentage of flower buds killed							
	Number of trees planted	Number killed before 1917	Dwarfs—less than 3 ft. high	Killed top and root	Killed to ground	Killed to snow	Trees examined in more detail	Two feet or more	Average of 1 foot	Average of 6 inches	Average of 2 inches	Tip or terminal bud	No injury	Dark brown	Medium brown	Slight brown	No injury	Bearing no flower buds	100 Per cent	95 Per cent	75 Per cent	50 Per cent	25 Per cent	10 Per cent	5 Per cent	No injury
P. americana × *P. americana*	20	1	..	..	..	..	19	..	..	..	..	13	6	..	1	..	18	2	..	..	..	..	..	..	..	17
P. americana × (*P. americana* × *P. triflora*)	106	42	10	3	..	2	49	..	..	5	3	25	16	6	3	10	30	8	2	..	..	..	1	2	4	32
P. americana × *P. triflora*	157	46	14	..	..	..	97	1	..	..	7	42	47	4	8	10	75	9	..	..	..	1	2	4	9	72
P. americana × *P. triflora* hybrids .	239	55	38	2	3	5	136	1	3	8	19	79	26	14	36	22	64	41	1	2	..	5	..	1	7	79
(*P. americana* × *P. triflora*) × (*P. americana* × *P. triflora*)	24	5	3	..	..	1	15	..	..	..	..	9	6	..	2	..	13	2	..	..	..	1	..	..	1	11
(*P. americana* × *P. triflora*) × *P. triflora*	57	14	2	3	1	..	37	1	1	3	6	16	10	16	9	2	10	13	9	5	2	1	1	1	..	5
(*P. americana* × *P. triflora*) × *P. triflora* hybrids	77	24	8	1	3	11	30	3	2	2	5	16	2	17	9	4	..	7	8	4	2	3	..	2	..	4
P. nigra × (*P. americana* × *P. triflora*)	27	14	5	..	..	..	8	..	..	..	..	..	8	..	..	..	8	..	..	..	..	..	..	..	1	7
P. nigra × *P. triflora* hybrids	41	3	3	1	..	..	34	..	..	..	1	18	15	7	2	13	12	4	..	..	..	..	..	..	..	30
P. nigra × *P. triflora*	6	1	..	..	..	..	5	..	..	1	..	2	2	..	1	1	3	3	..	..	..	..	..	1	..	1
P. besseyi × *P. triflora*	11	3	..	..	..	4	4	3	..	..	..	..	1	4	..	..	..	..	..	..	..	..	1	2	..	1
P. besseyi × *P. triflora* hybrids ...	87	29	13	1	4	10	30	5	6	1	3	4	11	15	12	3	..	..	..	..	2	7	4	12	4	1
P. besseyi hybrids × *P. americana* .	25	4	3	..	..	1	17	..	..	1	2	6	8	3	1	9	4	2	..	..	..	..	..	..	2	13
P. besseyi hybrids × *P. nigra*	6	2	1	..	..	..	3	..	..	..	..	1	2	..	..	..	3	..	..	..	..	..	..	..	1	2
P. besseyi hybrids × (*P. americana* × *P. triflora*)	31	6	7	2	2	4	10	..	2	..	..	6	2	3	3	2	2	1	1	..	..	1	1	4	2	..
P. besseyi hybrids × *P. triflora* ...	128	25	14	4	14	16	55	9	1	3	11	25	6	34	16	4	1	8	1	..	1	5	11	18	9	2
P. besseyi hybrids × *P. triflora* hybrids	146	61	24	9	12	6	34	4	5	1	7	14	3	23	6	5	..	4	2	1	1	4	13	5	4	..
P. pissardi × *P. americana*	2	..	1	..	..	..	1	..	..	1	..	..	..	..	..	..	1	1	..	..	..	..	..	..	..	..
P. pissardi × *P. besseyi*	5	3	1	..	..	..	1	1	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	1
P. pissardi × (*P. americana* × *P. triflora*)	115	24	17	22	20	11	21	1	4	2	6	8	..	15	6	..	..	10	3	2	2	1	..	..	..	3
P. pissardi × *P. besseyi* hybrids ...	12	4	2	1	..	3	2	..	1	1	..	..	..	1	1	..	..	1	..	..	..	1	..	..	..	..
Total	1322	366	166	49	59	74	608	29	25	29	70	284	171	163	116	85	244	116	27	14	10	30	34	52	44	281

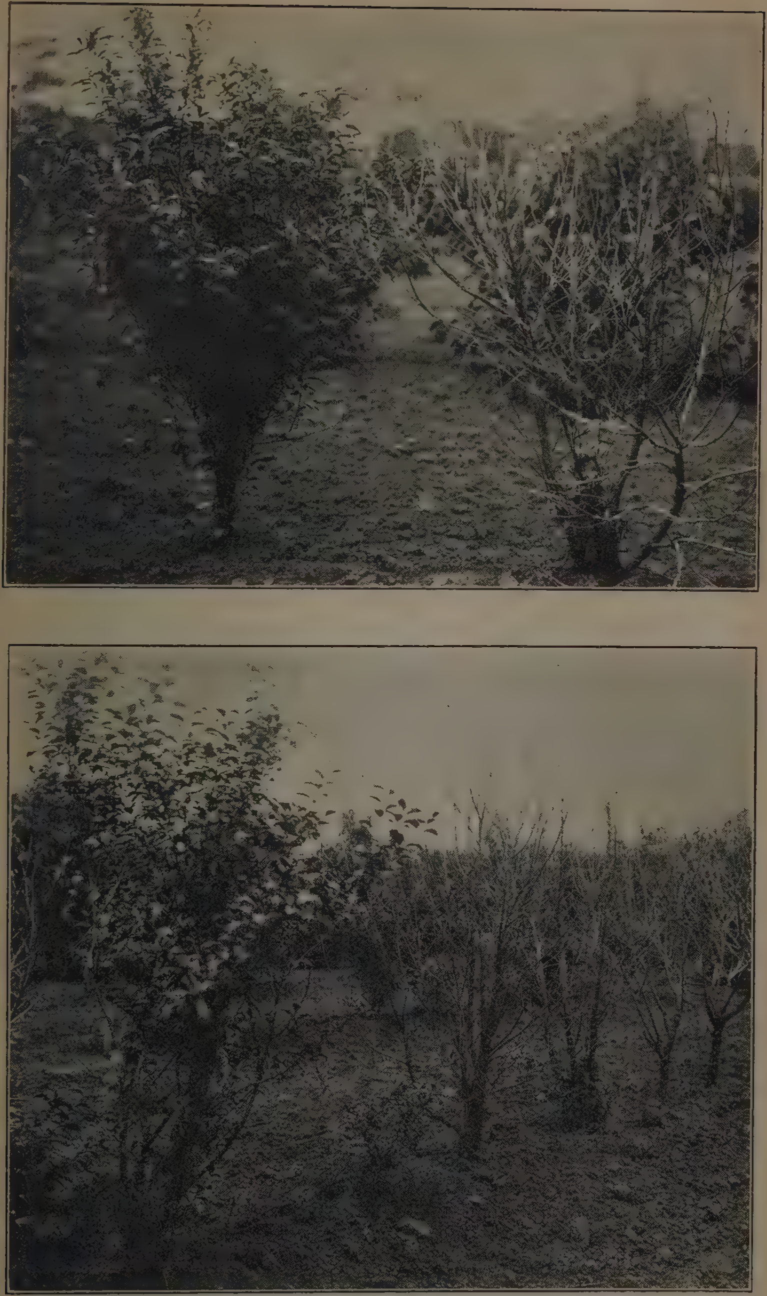


Fig. 3. Upper: Differences in Killing Encountered in Progeny. At Left, Growing at the Tip; at Right, Killed to the Ground

Lower: *P. besseyi* × Climax, Showing Effect of Winter Killing on Tender Progeny

The first tree is growing at the tip, the next is a dwarf; the third was killed outright; the fourth was killed to the ground; and the last three were killed outright.

DISCUSSION AND CONCLUSIONS

When such factors as the length of growing season, maturity, dormancy, the rest period, nutrition, precipitation, temperature changes, temperature extremes, and snow protection are taken into consideration, it will be seen that the reaction of plum seedlings to their environment, expressed here in terms of winter injury, is by no means a simple relationship. The relative influence which any one of these factors has upon injury or killing can not be separated definitely from that of the others, but all acting together determine the ability of a particular seedling to withstand winter conditions.

From one standpoint the environment may be regarded as the primary consideration in hardiness and the genetic constitution secondary, or vice versa. For instance, it is possible to picture extremes in winter weather which would be so severe as to be beyond the endurance of *Prunus*. On the other hand, winter conditions could be set forth which would not cause any injury to such seedlings as those under consideration. As a matter of fact, however, under fairly comparable conditions during the winter of 1917-18, the seedlings under observation reacted so differently, that considering the extremes, some were killed and others were uninjured. With these seedlings, therefore, it appears that the differences in individual response to winter conditions were a result, for the most part, of their genetic constitution.

The relatively close correlation in the injury to the various parts of the tree indicates that the hardiness of each part is determined by a more general condition. At least no individuals were found in which the flower buds were hardy and the bark or wood severely injured. Killing in the terminal bud under conditions of late growth on otherwise hardy trees was no doubt due, for the most part, to the late growth resulting from cultivation. There was some difference in the extent of killing back accompanying a given degree of browning in the bark and wood, but the greatest killing back was found associated with the severest injury to them.

The great differences in survival value shown by these seedlings may be taken as an illustration of the manner in which natural selection builds up hardy forms. Altho the process of eliminating the tender forms has extended over only a few winters, the killing so far has left the hardier trees only for reproduction. Darwin (1859) expresses the difference in hardiness encountered in native species in these words—"We have evidence with some few plants, of their becoming to a certain extent, naturally habituated to different temperatures; that is, they become acclimatized; thus the pines and rhododendrons, raised from seed collected by Dr. Hooker from the same species growing at different heights on the Himalayas, were found to possess in this country different constitutional powers of resisting cold."

With the plum seedlings in question it is probable that the more tender seedlings among both the dwarfs and standard trees were killed during the winters before 1917-18. By referring to Table X it will be seen that there were, in all, 366 trees out of 1322 which were killed before the test winter, compared with 49 out of 790 which were killed during it. Considering the fact that the greater killing of young trees took place in milder winters, it appears reasonable to assume that these were the less hardy of the group.

If natural selection operates in this way to eliminate the less hardy individuals of a species in a given region, the hardier would give rise to new individuals which in turn would be subjected to a similar selection process. In this way it would appear that natural selection would tend to bring a species in a given region toward the homozygous condition as far as hardiness is concerned.

At this point it will be interesting to note the relative hardiness of the F_1 in crosses where varieties of *P. americana, P. nigra, P. triflora, and P. besseyi* enter. When *P. americana* is crossed with *P. americana* the F_1 seedlings are practically all hardy, especially in the buds, bark, and wood. The terminal buds, however, were injured in some instances. On the other hand, where *P. americana* was crossed with *P. triflora* hybrids, there is considerable segregation in hardiness in the F_1, with a portion of the seedlings in each cross classified in the columns headed "no injury." The dispositions of the crosses with *P. nigra* are quite comparable to those with *P. americana*. When *P. besseyi* is substituted for *P. americana* or *P. nigra* in the crosses with *P. triflora,* a much larger proportion of the seedlings are grouped under the headings indicating various degrees of injury. In crosses in which *P. pissardi* was used with *P. besseyi* or with *P. americana* × *P. triflora* hybrids, a still smaller proportion are hardy.

Without going into further detail, it may be stated that there have not been outstanding differences in the hardiness of the F_1 where different variety combinations representing the same species have been made. There are, however, distinct differences in the value of the species in securing hardy progeny. *P. nigra* and *P. americana* rank first as parents in the percentage of hardy progeny wherever they have been used with *P. besseyi,* of less value.

In the progeny produced from crossing hardy *P. americana* varieties with the tender *P. triflora* varieties, it will be seen that while a relatively large number of seedlings are hardy many were killed before 1917-18, and that still others are classified as semihardy. This raises the question as to whether or not the hardy forms like *P. americana* and *P. nigra* are homozygous for hardiness. The seedlings of the cross *P. americana* × *P. americana* in Table VI, altho one of the hardiest progeny under test, were injured slightly in the terminal buds, and in one instance in the wood. Only one individual in this combination was killed before 1917. The extent of injury to the terminal buds may, however, be looked upon partly as an index of immaturity, as these plots were under cultivation. Nevertheless, the progeny of this cross fall well within the limits of commercial hardiness for this region. Considering the source of the varieties used as parents it appears that in *P. americana* natural selection has gone far toward eliminating the tenderer combinations and that when this species is crossed with forms like *P. triflora* the range in hardiness encountered in the F_1 is a result primarily of the genetic constitution of *P. triflora*. Such evidence indicates that in the northern habitat of *P. americana* and *P. nigra,* natural selection has isolated the hardier forms by eliminating the individuals possessing the tender factor combinations.

The question is now approached as to what extent the progeny under study are representative of possible factor combinations of the parents used. Fortunately the details of reproduction in Prunus have been worked out sufficiently to throw some light upon this phase of the problem. During gametogenesis an extensive suppression of gametes takes place in all interspecific varieties (Dorsey 1919). In the processes which take place at bloom a further elimination of gametes occurs, because flower production in the plum is so profuse that it is impossible, owing to the crowding of the fruit and the limits to the strength of the tree, for more than 5 to 10 per cent of the flowers to set and to mature. The first and second drops mark the end of the suppression of female gametes. Likewise, the loss of pollen grains during dehiscence and the differential germination of pollen on the stigmas terminates the period of loss in the male gametes. Following fertilization, in the June drop, and during the subsequent loss before maturity, there is an extensive elimination of zygotes. Finally, in the seedbed there is a further loss of zygotes in the seeds which fail to germinate. The series may be extended also to include the loss of seedlings before and after planting in the test plots, because this loss reduces the total number of individuals available for study. It seems, therefore, that in the suppression or loss of gametes, zygotes, and seedlings there is a mechanism, as well as an opportunity, for the elimination of many genetic combinations.

In view of the extent of the suppression series outlined above, it is difficult to evaluate either the extent or the direction of the elimination of possible genetic combinations, if such occur. In fact it would appear that this question can not be settled until the genetic studies of the genus are further advanced, especially along the line of back crosses or crosses between individuals of the same progeny, and then only with a large number of seedlings available.

Even if the evidence, therefore, as to the possible range of genetic combinations is incomplete, and this study deals only with the factor or group of factors determining hardiness, nevertheless, two characteristics of this material command attention in this connection. In the first place the test to which these seedlings were subjected during the winter of 1917-18, shows that the individuals of most of the F_1 progenies vary in the degree of hardiness possessed. This is particularly true of the combinations in which one parent is hardy and the other semihardy or tender. The response of some of the progenies, such as Zekanta × *P. americana* (Table II) representing a hardy combination, and Wohonka × *P. pissardi,* (Table IX and Fig. 2) representing a tender combination, shows more of an approach to uniformity typical of the F_1 of homozygous parents. But, in the cross Zekanta × *P. americana,* it should not be forgotten that the winter in question may not have been sufficiently severe to bring about differential injury. In the second place, in many of the combinations, as illustrated in those of Table V, there was an extensive elimination of the tender individuals previous to 1917, leaving populations which are classified for the most part under the headings of least injury. In some crosses only the hardy individuals are left, but in others both extremes are represented in the trees which survived, when those seedlings severely injured during 1917-18 are included in the series. In still other progenies the middle classes are left more or less vacant as a result of the grouping at the extremes. As to just what disposition would have been made of those seedlings which were killed before 1917, had they lived until the test winter, can not, of course, be definitely stated, but it is probable that they would have been classified for the most part with the group which were injured more or less severely, making the distribution in the different classes more uniform.

It should be remembered that the species included in this investigation are cross-pollinated. This is brought about in the wild as well as under cultivation by self-sterility and, to some extent by cross-sterility, both of which prevent the building up of homozygous forms except in so far as this is accomplished by winter killing. That this has a bearing upon the genetic constitution of the varieties used in the crosses is supported by two lines of evidence. (1) By referring to Table IV in "A Study of Sterility in the Plum" (Dorsey, 1919), it will be seen that in the varieties representing a single species, such as Blush, Ironclad, Ocheeda, Wyant, and three wild seedlings representing *P. americana,* there is considerable pollen abortion. The same may be said of

Aitkin, Cheney, and three wild seedlings representing *P. nigra,* Burbank representing *P. triflora,* and also the native forms listed from *P. besseyi* and *P. pennsylvanica.* (2) Considerable variation can be found in many of the tree and fruit characters of wild seedlings. In fact, the first named varieties of *P. nigra* and *P. americana* are nothing more than named wild seedlings selected from many thousands on account of some conspicuous variation in the fruit. Even a casual study of seedlings of *P. besseyi* in the nursery will show the same thing to be true of this species. The different varieties of *P. triflora* may be taken as evidence that this species, like our native forms, is heterozygous for many characters. This point has also been followed in seedlings at the Minnesota station from many other varieties of *Prunus.* Without presenting the evidence, therefore, it may be stated in this connection that there are sufficient differences between the different individuals of progeny representing any one species when fruit, tree, leaf, form, and vigor are studied critically, to warrant varietal recognition to any one of them. It may be concluded, then, that both the pollen condition and the character expression of the varieties representing a single species, to say nothing of interspecific varieties, show that the cross-pollination, brought about by self- and cross-sterility, maintains considerable heterozygosity in *Prunus.*

What effect has this heterozygosity of the species upon the F_1? Does the gamete suppression noted above have a bearing upon zygote suppression at the June drop, or on embryo suppression in the seedbed where so many seeds fail to germinate? Where records were kept of the seed germination in the different crosses—especially in the interspecific crosses—there was always considerable variation in the percentage which grew and, while the whole problem of seed germination is now generally regarded as extremely complex and no particular attempt was made in this instance to control the conditions under which these seeds were stratified, this variation in germination appears to be determined to a very large extent by genetic influence.

Referring now to those crosses in which the varieties used as parents are pure for their respective species, it will be seen that combinations are possible which involve one or two species, i.e., intra- or interspecific crosses. In such crosses in the F_1 zygote the chromosome combination may represent a single species or two. In the latter case there is no opportunity for a recombination series in the parental chromosomes as set forth by Babcock and Clausen (1918) as taking place in the F_2 because each individual in the F_1 contains an equal number of chromosomes from each parent. It would appear, therefore, that in the crosses of this category the progeny could be regarded as representing the possible character combinations except in so far as influenced by the gamete suppression arising from heterozygosity within the species.

On the other hand, when the parents include interspecific varieties a number of combinations are possible. If only one parent is an interspecific variety, the suppression of gametes can be influenced by the heterozygosity of the species and also by the recombination series of parental gametes. If both parents are interspecific varieties, the recombination of parental chromosomes in the F_1 becomes extremely complex if influenced by the heterozygosity of the species as well as by the partial suppression of a recombination series. The distribution of some of the progeny at the extremes of the hardiness classes suggests that in the recombination series chromosome combinations are encountered which are unable to function as zygotes. It is probable, therefore, that the heavy loss of seeds and seedlings has a genetic background in the recombination series and that the possible combinations of the factors for hardiness do not gain normal expression on account of the extensive suppression at various points in the life history.

As stated in the introduction, the general point of attack in this investigation has been to cross hardy native varieties with others less hardy but possessing better fruit characteristics, with the object of obtaining seedlings possessing both hardiness and superior fruit. Recognizing at the outset that hardiness was the limiting factor in the final selections, this material has been studied critically with the object of determining the species from which individuals possessing sufficient hardiness combined with desirable fruit characters, could be obtained. As to the inheritance of hardiness, even with the limitations which self- and cross-sterility impose upon the technic of breeding when dealing with heterozygous material of this kind, certain questions can be answered for *Prunus* which will serve as a guide in the future in the application of genetics to plum breeding.

Aside from the more technical aspects of the subject, conclusions can be drawn from the data presented which furnish a workable basis for breeding for hardiness in plums. From the applied standpoint it is important to know when a hardy variety is crossed with a tender one, whether the F_1 will all be hardy, all tender, all intermediate, or whether all degrees of hardiness between the parents will be encountered. By referring to the various combinations in the tables it will be seen, in general, that where hardiness is present in both parents, the progeny are hardy; where both parents are tender the progeny are tender; and that where extremes are encountered in the hardiness of the parents, gradations in hardiness occur in the progeny, altho the intermediate individuals are not typically represented as would be expected in an uninterrupted series of multiple factors. Considering the number of species under investigation in this experiment it would appear that these findings will form a workable basis for plum breeders to follow where hardiness is a limiting factor.

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